Low Impact Development Resource Guide
June 2005

This LID educational initiative is a project of the Makah Tribe, with support from the Puget Sound Action Team's Public Involvement and Education Fund. Project team members include Sustainable Community Solutions and Magnusson-Klemencic

Sustainable Community Solutions

MAGNUSSON KLEMENCIC ASSOCIATES

MAKAH TRIBE

PUGET SOUND ACTION TEAM
Office of the Governor

Low Impact Development Resource Guide

The Low Impact Development (LID) approach, uses site design techniques that store, infiltrate, evaporate, and detain runoff, to ensure that a site's post-development hydrologic functions mimic those in its pre-development state. Use of these techniques helps to reduce off-site runoff and ensure adequate groundwater recharge. These techniques typically constitute a "de-centralized" strategy of storm water management. This guide identifies where additional information can be found about low-impact development strategies and practices.

Overall Site Layout and Design Strategies

Documents:

"Low-Impact Development Design Strategies: An Integrated Design Approach." Prepared by Prince George's County, Maryland, Department of Environmental Resources. June 1999.
Available from http://www.lowimpactdevelopment.org/publications.htm
This document was prepared by the Prince George's County Maryland Department of Environmental Resources Programs and Planning Division, with assistance from EPA.

"The Practice of Low Impact Development", Prepared for: U.S. Department of Housing and Urban Development, Office of Policy Development and Research, Washington, D.C. July 2003. Available from http://www.lowimpactdevelopment.org/publications.htm

"Design: Low Impact Development Manual", UFC 3-210-10 25 October 2004. Available from http://www.epa.gov/owow/nps/lid/
This manual was created by the Department of Defense (DoD) United Facilities Criteria (UFC). The UFC provides guidance for integrating LID planning and design into a facility's regulatory and resource protection programs.

"Low Impact Development: Technical Guidance Manual for Puget Sound," January 2005. Puget Sound Action Team. Available from
http://www.psat.wa.gov/Publications/LID_tech_manual05/lid_index.htm

Websites:

Puget Sound Action Team
This comprehensive website provides extensive information about LID applications in Washington and has many links to case studies, design examples, and design manuals.
http://www.psat.wa.gov/Programs/LID.htm

Low Impact Development (LID) Center
A non-profit organization balancing growth and environmental integrity.
www.lowimpactdevelopment.org

United States Environmental Protection Agency
www.epa.gov/owow/nps/lid/

Integrated Management Practices

Better Site Design

The following excerpts are from The Center for Watershed Protection, http://www.cwp.org/better_site_design.htm

This section provides some basic information about better site design and why it's important. For more detailed information, you might want to read the "Introduction to Better Site Design" article (.pdf format), or visit our Stormwater Manager's Resource Center at www.stormwatercenter.net to see slideshows, additional articles and other better site design materials. As well, check out our Builders for the Bay project to see how the Center is helping to make better site design happen in the Chesapeake Bay region.

Few watershed management practices simultaneously reduce pollutant loads, conserve natural areas, save money, and increase property values. Indeed, if such “wonder practices” were ever developed, they would certainly spread quickly across the nation. As it turns out, these practices have existed for years. Collectively called “better site design,” the techniques employ a variety of methods to reduce total paved area, distribute and diffuse stormwater, and conserve natural habitats.

Better site design is a fundamentally different approach to residential and commercial development. It seeks to accomplish three goals at every development site: to reduce the amount of impervious cover, to increase natural lands set aside for conservation, and to use pervious areas for more effective stormwater treatment. To meet these goals, designers must scrutinize every aspect of a site plan— its streets, parking spaces, setbacks, lot sizes, driveways, and sidewalks— to see if any of these elements can be reduced in scale. At the same time, creative grading and drainage techniques reduce stormwater runoff and encourage more infiltration.

Why is it so difficult to implement better site design in so many communities? The primary reason is the outdated development rules that collectively govern the development process: a bewildering mix of subdivision codes, zoning regulations, parking and street standards, and drainage regulations that often work at cross-purposes with better site design. Few developers are willing to take risks to bend these rules with site plans that may take years to approve or that may never be approved at all. In 1997, a national site planning roundtable was convened to address ways to encourage better site design techniques in more communities. The participants represented the diverse mix of organizations that affect the development process and provided the technical and real-world experience to make better site design happen. After two years of discussion, the roundtable endorsed 22 better site design techniques that offer specific guidance that can help achieve one of the basic better site design goals. These techniques are grouped into three areas:

1. Residential Streets and Parking Lots
2. Lot Development
3. Conservation of Natural Areas

Site Planning Model Development Principles

The twenty-two model development principles provide design guidance for economically viable, yet environmentally sensitive development. Our objective is to provide planners, developers, and local officials with benchmarks to investigate where existing ordinances may be modified to reduce impervious cover, conserve natural areas, and prevent stormwater pollution. These development principles are not national design standards. Instead, they identify areas where existing codes and standards can be changed to better protect streams, lakes and wetlands at the local level. The development principles are divided into the three following areas:

- Residential Streets and Parking Lots (Habitat for Cars)

- Lot Development (Habitat for People)
- Conservation of Natural Areas (Habitat for Nature)

Each principle is presented as a simplified design objective. Actual techniques for achieving the principle should be based on local conditions.

Residential Streets and Parking Lots (Habitat for Cars)

1. Design residential streets for the minimum required pavement width needed to support travel lanes; on-street parking; and emergency, maintenance, and service vehicle access. These widths should be based on traffic volume.

2. Reduce the total length of residential streets by examining alternative street layouts to determine the best option for increasing the number of homes per unit length.

3. Wherever possible, residential street right-of-way widths should reflect the minimum required to accommodate the travel-way, the sidewalk, and vegetated open channels. Utilities and storm drains should be located within the pavement section of the right-of-way wherever feasible.

4. Minimize the number of residential street cul-de-sacs and incorporate landscaped areas to reduce their impervious cover. The radius of cul-de-sacs should be the minimum required to accommodate emergency and maintenance vehicles. Alternative turnarounds should be considered.

5. Where density, topography, soils, and slope permit, vegetated open channels should be used in the street right-of-way to convey and treat stormwater runoff.

6. The required parking ratio governing a particular land use or activity should be enforced as both a maximum and a minimum in order to curb excess parking space construction. Existing parking ratios should be reviewed for conformance taking into account local and national experience to see if lower ratios are warranted and feasible.

7. Parking codes should be revised to lower parking requirements where mass transit is available or enforceable shared parking arrangements are made.

8. Reduce the overall imperviousness associated with parking lots by providing compact car spaces, minimizing stall dimensions, incorporating efficient parking lanes, and using pervious materials in spillover parking areas where possible.

9. Provide meaningful incentives to encourage structured and shared parking to make it more economically viable.

10. Wherever possible, provide stormwater treatment for parking lot runoff using bioretention areas, filter strips, and/or other practices that can be integrated into required landscaping areas and traffic islands.

Lot Development (Habitat for People)

11. Advocate open space design development incorporating smaller lot sizes to minimize total impervious area, reduce total construction costs, conserve natural areas, provide community recreational space, and promote watershed protection.

12. Relax side yard setbacks and allow narrower frontages to reduce total road length in the community and overall site imperviousness. Relax front setback requirements to minimize driveway lengths and reduce overall lot imperviousness.

13. Promote more flexible design standards for residential subdivision sidewalks. Where practical,

consider locating sidewalks on only one side of the street and providing common walkways linking pedestrian areas.

14. Reduce overall lot imperviousness by promoting alternative driveway surfaces and shared driveways that connect two or more homes together.

15. Clearly specify how community open space will be managed and designate a sustainable legal entity responsible for managing both natural and recreational open space.

16. Direct rooftop runoff to pervious areas such as yards, open channels, or vegetated areas and avoid routing rooftop runoff to the roadway and the stormwater conveyance system.

Conservation of Natural Areas (Habitat for Nature)

17. Create a variable width, naturally vegetated buffer system along all perennial streams that also encompasses critical environmental features such as the 100-year floodplain, steep slopes and freshwater wetlands.

18. The riparian stream buffer should be preserved or restored with native vegetation. The buffer system should be maintained through the plan review delineation, construction, and post-development stages.

19. Clearing and grading of forests and native vegetation at a site should be limited to the minimum amount needed to build lots, allow access, and provide fire protection. A fixed portion of any community open space should be managed as protected green space in a consolidated manner.

20. Conserve trees and other vegetation at each site by planting additional vegetation, clustering tree areas, and promoting the use of native plants. Wherever practical, manage community open space, street rights-of-way, parking lot islands, and other landscaped areas.

21. Incentives and flexibility in the form of density compensation, buffer averaging, property tax reduction, stormwater credits, and by-right open space development should be encouraged to promote conservation of stream buffers, forests, meadows, and other areas of environmental value. In addition, off-site mitigation consistent with locally adopted watershed plans should be encouraged.

22. New stormwater outfalls should not discharge unmanaged stormwater into jurisdictional wetlands, sole-source aquifers, or sensitive areas.

Documents:

"Site-Planning for Urban Stream Protection", Schueler, Thomas R., Metropolitan Washington Council of Governments and Center for Watershed Protection. 1995.

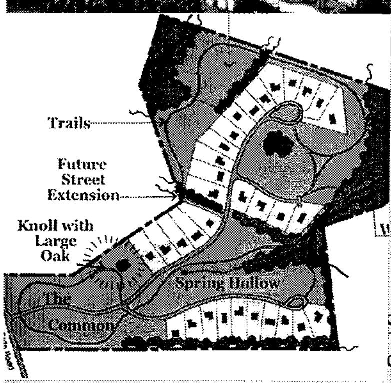
"The Practice of Watershed Protection", ", Schueler, Thomas R. & Holland, Heather K., Metropolitan Washington Council of Governments and Center for Watershed Protection. 2000.

Low Impact Development strategies use careful site design and decentralized stormwater management to reduce the environmental footprint of new growth. This approach improves water quality, minimizes the need for expensive pipe-and-pond stormwater systems, and creates more attractive developments.

MASSACHUSETTS **LOW IMPACT DEVELOPMENT** TOOLKIT

FACT SHEET #8

LOW IMPACT SITE DESIGN



Overview

Conventional development strategies treat stormwater as a secondary component of site design, usually managed with "pipe-and-pond" systems that collect rainwater and discharge it off site. In contrast, Low Impact Development embraces hydrology as an integrating framework for site design, not a secondary consideration. Existing conditions influence the location of roadways, buildings, and parking areas, as well as the nature of the stormwater management system.

LID site design is a multi-step process that involves identifying important natural features, placing buildings and roadways in areas less sensitive to disturbance, and designing a stormwater management system that creates a relationship between development and natural hydrology. The attention to natural hydrology, stormwater "micromanagement," nonstructural approaches, and landscaping results in a more attractive, multifunctional landscape with development and maintenance costs comparable to or less than conventional strategies that rely on a pipe-and-pond approach.

Sensitive site landscaping is an important component of Low Impact Development. Ecological landscaping strategies seek to minimize the amount of lawn area and enhance the property with native, drought-resistant species; as a result, property owners use less water, pesticides, and fertilizers. The maintenance of vegetated buffers along waterways can also enhance the site and help protect water quality.

Applications and Design Principles

LID site planning is similar to Conservation Subdivision Design (CSD) process, though LID site planning can be applied to both residential and nonresidential development as well as redevelopment projects. The four step process of CSD (identify conservation areas; locate home sites; align streets and trails; draw in lot lines) provides a serviceable framework for the LID site design process, which involves designing a stormwater management system in conjunction with the second and third steps of the CSD process.

Management Objectives

- Develop a site plan that reflects natural hydrology.
- Minimize impervious surfaces.
- Treat stormwater in numerous small, decentralized structures.
- Use natural topopgraphy for drainageways and storage areas.
- Preserve portions of the site in undisturbed, natural conditions.
- Lengthen travel paths to increase time of concentration and attenuate peak rates.
- Use "end of pipe" treatment structures only for quantity/rate controls of large storms.

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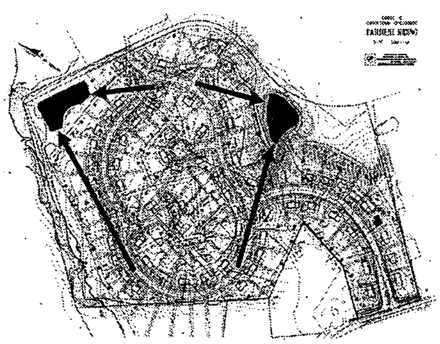
Site Analysis

An LID site planning strategy will begin with an assessment of environmental and hydrologic conditions on a site and identification of important natural features such as streams and drainageways, floodplains, wetlands, recharge groundwater protection areas, high-permeability soils, steep slopes and erosion-prone soils, woodland conservation areas, farmland, and meadows. This investigation will help to determine what "conservation areas" should be protected from development and construction impacts, and what site features (such as natural swales) might be incorporated into the LID stormwater system.

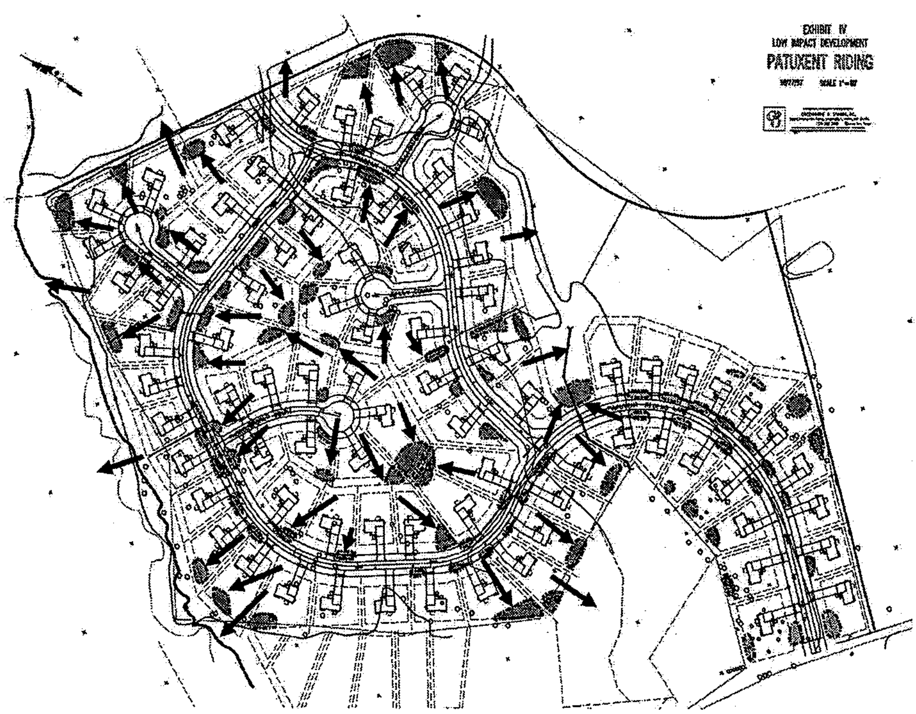
The site analysis will also identify a "development envelope" where development can occur with minimal impact to hydrology and other ecologic, scenic, or historic features. In general, this will include upland areas, ridge lines and gently sloping hillsides, and slowly permeable soils outside of wetlands. The remainder of the site should be left in a natural undisturbed condition. It is important to protect mature trees and to limit clearing and grading to the minimum amount needed for buildings, access, and fire protection; lawn areas increase runoff that must be managed, whereas preservation of wooded areas reduces the volume of stormwater that must be treated. Construction activity, including stockpiles and storage areas, should be confined to those areas that will be permanently altered, and the construction fingerprint should be clearly delineated.

Locate Development and Roadways

Based on the development envelope from the site analysis, developers and their consultants should prepare potential site development layouts. These layouts should minimize total impervious area; reflect the existing topography; and utilize existing drainageways, swales, depressions, and storage areas in their natural state. The goal is to minimize the amount of runoff that must be treated in a stormwater management system.



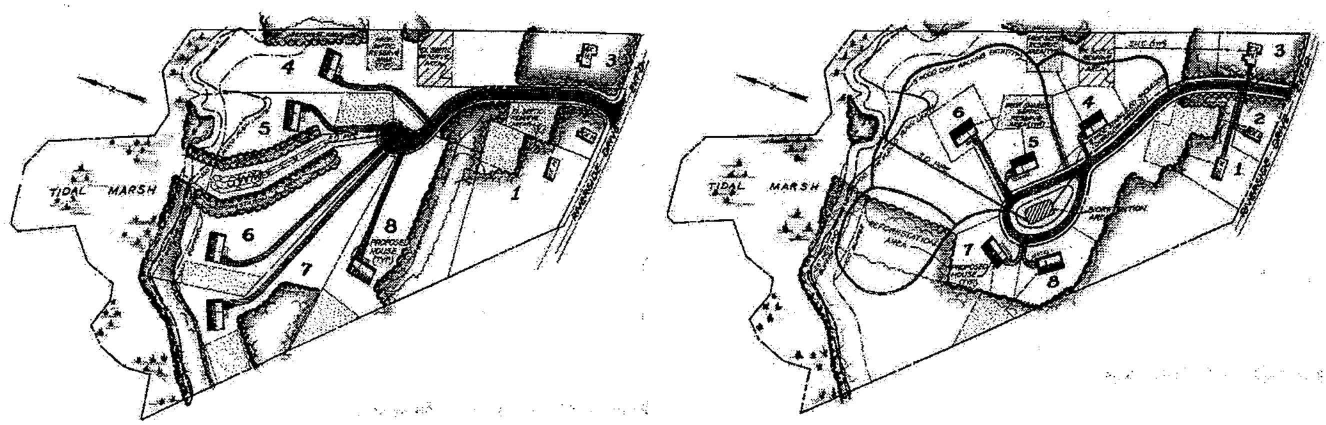
In order to reduce site coverage but not square footage, site development layouts may include buildings clustered together, parking structures (instead of lots), or taller buildings with a smaller footprint relative to floor area. However, these strategies may conflict with local land use regulations that address density, height, frontages, and lot coverage, so consultation with local officials is critical to help them



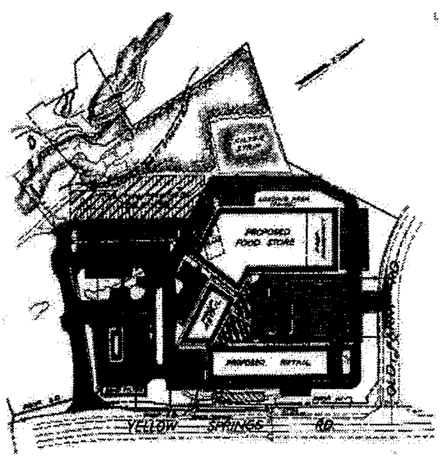
Conventional development strategies (above) concentrate stormwater runoff in storm sewers and deliver it to a few large ponds for treatment at the end of the pipe. Low Impact Development (right) seeks to create multiple small "sub-watersheds" on a site and treats runoff close to the source in smaller structures.

Cover, top: A clustered subdivision with smaller setbacks and preserved natural areas (left) contrasts with a conventional subdivision where all the trees have been removed.

Cover, bottom: A schematic diagram of a conservation subdivision design plan.



Above: Two alternative designs for an eight-lot subdivision. The low-impact on the right uses shared driveways and a one-way loop road to minimize impervious surfaces. The preservation of natural areas and the creation of trails adds value to the properties. *Images: Center for Watershed Protection*



Above: A commercial site design that uses clustering and multiple parking areas to protect water resources and provide opportunities for low impact stormwater management techniques. This design provides the same square footage and parking spaces as a conventional design that encroaches on a nearby marsh (at top.) *Image: Center for Watershed Protection*

understand the rationale for the proposed development plan. Other strategies for minimizing impervious surfaces include reduced road widths, smaller parking areas, permeable paving, and green roofs, all of which are described in greater detail in other LID fact sheets.

Once approximate building locations are known, general roads alignments can be identified. Roads should not cross steep slopes, where cutting and filling will unnecessarily disturb drainage patterns; instead, roadways should follow existing grades and run along existing ridge lines or high points. As a rule of thumb, roadways should run parallel to contours on gentle slopes, and perpendicular to the contours on steeper slopes. Large expanses of parking should be broken up into multiple smaller parking lots; this will help to reduce grading on hilly sites, since separate parking areas can be placed at different elevations.

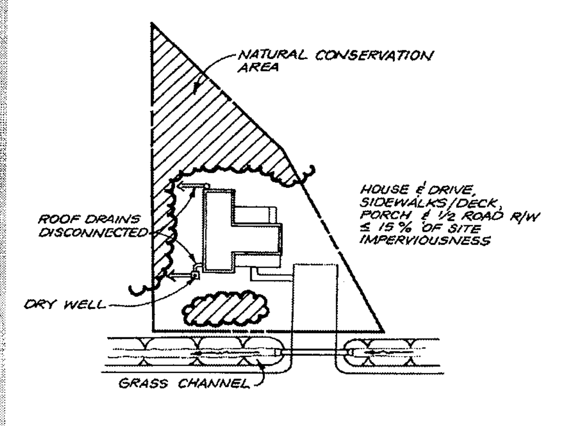
Create a Decentralized Stormwater System

The actual location of buildings and the alignment of roadways should be determined in conjunction with the design of the stormwater management system. The goal of this process is to minimize "directly connected impervious area"—those impervious areas that drain directly into a pipe-and-pond stormwater system. Designers should seek to maintain or create small sub-watersheds on the site and "micromanage" the runoff from these sub-watersheds in small decentralized structures, such as swales, bioretention areas, infiltration structures, and filter strips. Paved surfaces should be graded and crowned so that they form multiple "mini-watersheds;" the runoff from each small drainage area should to a different bioretention area, swale, or filter strip. Roof runoff should be sent to rain barrels, cisterns, dry wells, and vegetated areas via level spreaders.

LID site design should also seek to maximize the travel time for stormwater runoff. Conventional pipe systems increase the speed of stormwater runoff, resulting in bigger peak discharge rates (and therefore bigger ponds) at the end of the pipe. In contrast, LID seeks to increase the time of concentration (the average travel time for rainfall) through a variety of techniques: retain stormwater in small structures close to the source (described above), provide as much overland or sheet flow as possible, use open drainage systems, provide long travel paths, and use vegetation to increase surface roughness.

Wherever possible, site design should use multifunctional open drainage systems such as vegetated swales or filter strips which also help to fulfill landscaping or green space requirements. Swales and conveyances can be designed to increase travel length (and time of concentration) with long flow paths that loop around parking lots or other features, rather than more direct routes. The result is increased infiltration and more attenuated peak discharge at the downstream end of the site—the peak comes later and is smaller.

LID stormwater structures (such as bioretention areas and infiltration trenches) should be sized to treat the stormwater from frequent, low intensity storms for



Above: A lot layout that uses infiltration, disconnection of rooftop runoff, conservation and vegetated swales to treat runoff.

water quality and infiltrate it into the ground or slowly release it; they should not be expected to completely manage the peak discharge rate or volume from large storms. Volume and rate controls at the downstream end of the site may still be necessary, but much smaller as a result of LID site design, decentralized stormwater management, and long travel paths.

Benefits and Effectiveness

- A comprehensive approach to site design is the most effective, cost-efficient means of minimizing stormwater runoff. A small investment in design at the outset of the project can reduce the expense associated with conventional stormwater systems.
- An LID site design approach based on natural hydrology will integrate the built space into the natural environment, giving the development integrity and an aesthetically pleasing relationship with the natural features of the site. Many LID stormwater management structures also serve as site landscaping.
- Developers who take a careful, comprehensive approach to site design—one that accommodates local development goals and protects important resources—run into less resistance from neighbors and local boards concerned about the aesthetic and environmental impacts of development.
- Site designs that involve a minimal amount of clearing, grading, and road/parking lot construction have lower overall site development costs.
- Small, distributed stormwater "micromanagement" techniques offer an advantage over centralized systems because one or more of the individual structures can fail without compromising the overall integrity of the stormwater management strategy for the site.
- Smaller decentralized facilities feature shallow basing depths and gentle side slopes, which reduce safety concerns as compared to deep ponds that must be fenced off.

Limitations

- The comprehensive LID site analysis and design process can rarely be conducted "in house" by developers; it requires the assistance of knowledgeable and qualified engineers and landscape architects.
- Some LID site designs that seek to cluster development and reduce lot coverage may conflict with local land use regulations or public perceptions about what type of development is desirable (a compact multistory building may be more visible than a single story building with a larger footprint.) Consequently, public education is necessary as well as cooperation among developers, advocates, and regulators who recognize the values of the LID site design approach.

Maintenance

There are no particular maintenance requirements associated with an LID site design, but by reducing the amount of stormwater runoff and associated stormwater management structures, LID can reduce the amount of maintenance required on a site.

Cost

The cost of an LID site design will vary depending on the site. The expertise necessary to create a comprehensive site plan may cost more than a simple engineering plan that ignores natural conditions and treats stormwater using a "pipe and pond" system; however, the resulting plans are commonly less expensive to construct and maintain, and the additional landscaping and aesthetic value of an LID development will add a premium to the sales price.

Additional References

Low Impact Development Design Strategies: An Integrated Design Approach; Prince George's County, Maryland, Department of Environmental Resources; June 1999. (available at http://www.epa.gov/owow/nps/lid/)

Better Site Design: A Handbook for Changing Development Rules in Your Community; Center for Watershed Protection; 1998

Site Planning for Urban Stream Protection; Thomas Schueler; Center for Watershed Protection; 1995.

Conservation Design for Subdivisions: A Practical Guide for Creating Open Space Networks; Randall Arendt; Island Press; 1996.

Site Analysis; James A. LaGro, Jr.; John Wiley and Sons; 2001

An Introduction to Better Site Design; Article 45 from Watershed Protection Techniques; Center for Watershed Protection; 2000

This publication is one component of the Massachusetts Low Impact Development Toolkit, a production of the Metropolitan Area Planning Council, in coordination with the I-495 MetroWest Corridor Partnership, with financial support from US EPA. The Massachusetts Low Impact Development Interagency Working Group also provided valuable input and feedback on the LID Toolkit.

Bioretention

The Puget Sound Action Team's "Low Impact Development: Technical Guidance Manual for Puget Sound," January 2005, covers bioretention extensively. This document provides specific design guidance for Washington, and presents numerous case studies. See http://www.psat.wa.gov/Publications/LID_tech_manual05/lid_index.htm

Prince George's County, Maryland, refined bioretention practices in the mid 1990's. Their website offers numerous resources to be used in planning, designing, and specifying bioretention facilities. See http://www.co.pg.md.us/Government/AgencyIndex/DER/PPD/LID/bioretention.asp

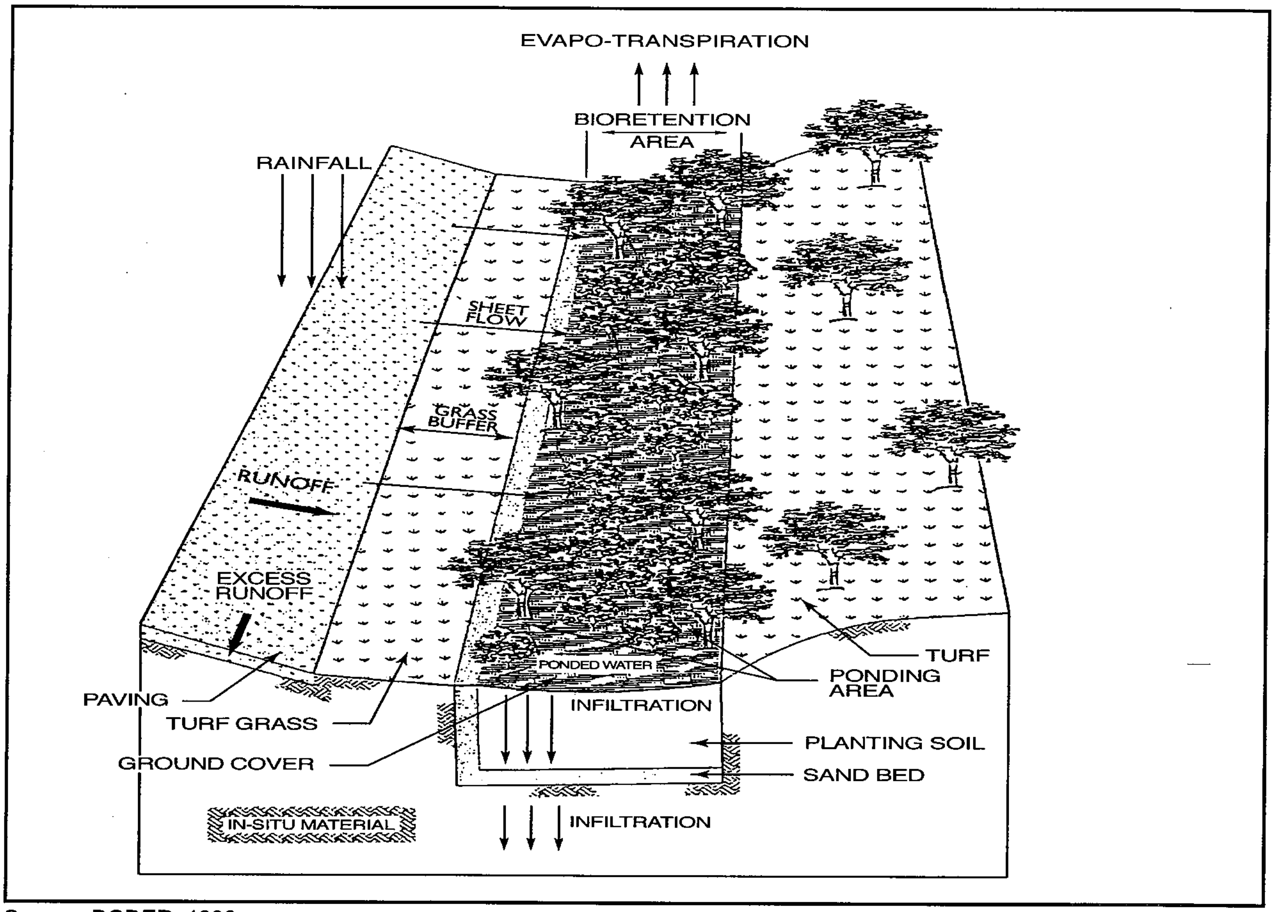
A Washington example of applied bioretention practices is the City of Seattle's Street-Edge-Alternatives ("SEA streets"). This pilot project was designed to provide drainage that more closely mimics the natural landscape prior to development than traditional piped systems. To accomplish this, the City reduced impervious surfaces to 11% less than a traditional street, provided surface detention in swales, and added over 100 evergreen trees and 1100 shrubs. Two years of monitoring show that SEA Street has reduced the total volume of stormwater leaving the street by 98% for a 2-year storm event. See http://www.ci.seattle.wa.us/util/About_SPU/
Drainage_&_Sewer_System/Natural_Drainage_Systems/Street_Edge_Alternatives/index.asp

United States Environmental Protection Agency
Office of Water Washington, D.C.
EPA 832-F-99-012 September 1999

Storm Water Technology Fact Sheet Bioretention

DESCRIPTION

Bioretention is a best management practice (BMP) developed in the early 1990's by the Prince George's County, MD, Department of Environmental Resources (PGDER). Bioretention utilizes soils and both woody and herbaceous plants to remove pollutants from storm water runoff. As shown in Figure 1, runoff is conveyed as sheet flow to the treatment area, which consists of a grass buffer strip, sand bed, ponding area, organic layer or mulch layer, planting soil, and plants. Runoff passes first over or through a sand bed, which slows the runoff's velocity, distributes it evenly along the length of the ponding area, which consists of a surface organic layer and/or ground cover and the underlying planting soil. The ponding area is graded, its center depressed. Water is ponded to a depth of 15 centimeters (6 inches) and gradually infiltrates the bioretention area or is



Source: PGDER, 1993.

FIGURE 1 BIORETENTION AREA

evapotranspired. The bioretention area is graded to divert excess runoff away from itself. Stored water in the bioretention area planting soil exfiltrates over a period of days into the underlying soils.

The basic bioretention design shown in Figure 1 can be modified to accommodate more specific needs. The City of Alexandria, VA, has modified the bioretention BMP design to include an underdrain within the sand bed to collect the infiltrated water and discharge it to a downstream sewer system. This modification was required because impervious subsoils and marine clays prevented complete infiltration in the soil system. This modified design makes the bioretention area act more as a filter that discharges treated water than as an infiltration device. Design modifications are also being reviewed that will potentially include both aerobic and anaerobic zones in the treatment area. The anaerobic zone will promote denitrification.

APPLICABILITY

Bioretention typically treats storm water that has run over impervious surfaces at commercial, residential, and industrial areas. For example, bioretention is an ideal storm water management BMP for median strips, parking lot islands, and swales. These areas can be designed or modified so that runoff is either diverted directly into the bioretention area or conveyed into the bioretention area by a curb and gutter collection system. Bioretention is usually best used upland from inlets that receive sheet flow from graded areas and at areas that will be excavated. The site must be graded in a manner that minimizes erosive conditions as sheet flow is conveyed to the treatment area, maximizing treatment effectiveness. Construction of bioretention areas is best suited to sites where grading or excavation will occur in any case so that the bioretention area can be readily incorporated into the site plan without further environmental damage. Bioretention should be used in stabilized drainage areas to minimize sediment loading in the treatment area. As with all BMPs, a maintenance plan must be developed.

Bioretention has been used as a storm water BMP since 1992. In addition to Prince George's County and Alexandria, bioretention has been used successfully at urban and suburban areas in Montgomery County, MD; Baltimore County, MD; Chesterfield County, VA; Prince William County, VA; Smith Mountain Lake State Park, VA; and Cary, NC.

ADVANTAGES AND DISADVANTAGES

Bioretention is not an appropriate BMP at locations where the water table is within 1.8 meters (6 feet) of the ground surface and where the surrounding soil stratum is unstable. In cold climates the soil may freeze, preventing runoff from infiltrating into the planting soil. The BMP is also not recommended for areas with slopes greater than 20 percent, or where mature tree removal would be required. Clogging may be a problem, particularly if the BMP receives runoff with high sediment loads.

Bioretention provides storm water treatment that enhances the quality of downstream water bodies. Runoff is temporarily stored in the BMP and released over a period of four days to the receiving water. The BMP is also able to provide shade and wind breaks, absorb noise, and improve an area's landscape.

DESIGN CRITERIA

Design details have been specified by the Prince George's County DER in a document entitled *Design Manual for the Use of Bioretention in Storm Water Management* (PGDER, 1993). The specifications were developed after extensive research on soil adsorption capacities and rates, water balance, plant pollutant removal potential, plant adsorption capacities and rates, and maintenance requirements. A case study was performed using the specifications at three commercial sites and one residential site in Prince George's County, Maryland.

Each of the components of the bioretention area is designed to perform a specific function. The grass buffer strip reduces incoming runoff velocity and filters particulates from the runoff. The sand bed also reduces the velocity, filters particulates, and spreads flow over the length of the bioretention area. Aeration and drainage of the planting soil are provided by the 0.5 meter (18 inch) deep sand bed. The ponding area provides a temporary storage location for runoff prior to its evaporation or infiltration. Some particulates not filtered out by the grass filter strip or the sand bed settle within the ponding area.

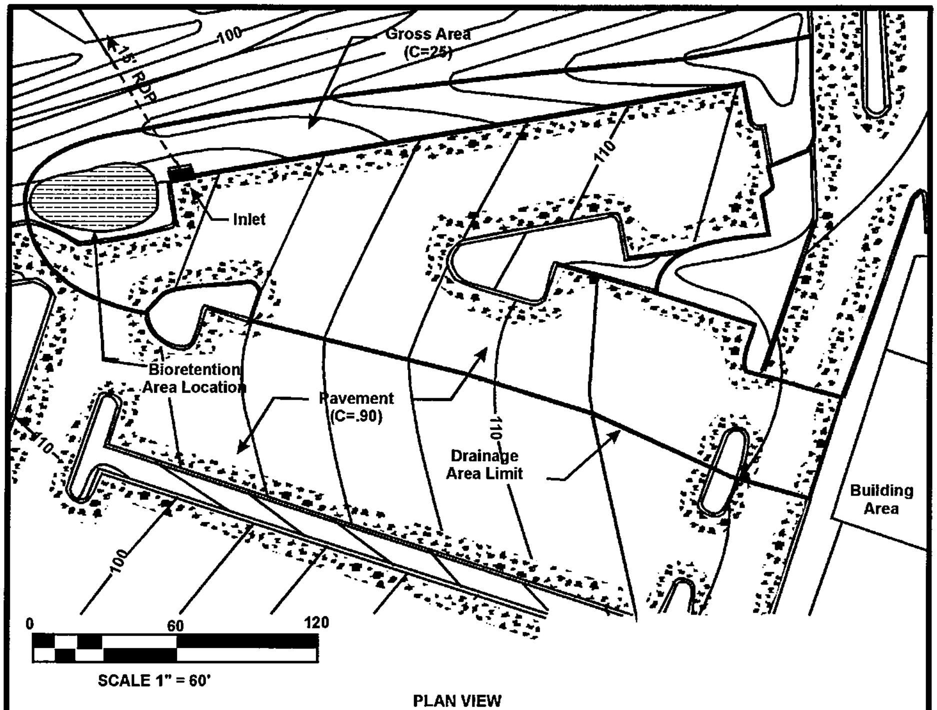
The organic or mulch layer also filters pollutants and provides an environment conducive to the growth of microorganisms, which degrade petroleum-based products and other organic material. This layer acts in a similar way to the leaf litter in a forest and prevents the erosion and drying of underlying soils. Planted ground cover reduces the potential for erosion as well, slightly more effectively than mulch. The maximum sheet flow velocity prior to erosive conditions is 0.3 meters per second (1 foot per second) for planted ground cover and 0.9 meters per second (3 feet per second) for mulch.

The clay in the planting soil provides adsorption sites for hydrocarbons, heavy metals, nutrients and other pollutants. Storm water storage is also provided by the voids in the planting soil. The stored water and nutrients in the water and soil are then available to the plants for uptake.

The layout of the bioretention area is determined after site constraints such as location of utilities, underlying soils, existing vegetation, and drainage are considered. Sites with loamy sand soils are especially appropriate for bioretention because the excavated soil can be backfilled and used as the planting soil, thus eliminating the cost of importing planting soil. An unstable surrounding soil stratum (e.g., Marlboro Clay) and soils with a clay content greater than 25 percent may preclude the use of bioretention, as would a site with slopes greater than 20 percent or a site with mature trees that would be removed during construction of the BMP. Bioretention can be designed to be off-line or on-line of the existing drainage system. The "first flush" of runoff is diverted to the off-line system. The first flush of runoff is the initial runoff volume that typically contains higher pollutant concentrations than those in the extended runoff period. On-line systems capture the first flush but that volume of water will likely be washed out by subsequent runoff resulting in a release of the captured pollutants. The size of the drainage area for one bioretention area should be between 0.1 and 0.4 hectares (0.25 and 1.0 acres). Multiple bioretention areas may be required for larger drainage areas. The maximum drainage area for one bioretention area is determined by the amount of sheet flow generated by a 10-year storm. Flows greater than 141 liters per second (5 cubic feet per second) may potentially erode stabilized areas. In Maryland, such a flow generally occurs with a 10-year storm at one-acre commercial or residential sites. The designer should determine the potential for erosive conditions at the site.

The size of the bioretention area is a function of the drainage area and the runoff generated from the area. The size should be 5 to 7 percent of the drainage area multiplied by the rational method runoff coefficient, "c," determined for the site. The 5 percent specification applies to a bioretention area that includes a sand bed; 7 percent to an area without one. An example of sizing a facility is shown in Figure 2. For this discussion, sizing specifications are based on 1.3 to 1.8 centimeters (0.5 to 0.7 inches) of precipitation over a 6-hour period (the mean storm event for the Baltimore-Washington area), infiltrating into the bioretention area. Other areas with different mean storm events will need to account for the difference in the design of the BMP. Recommended minimum dimensions of the bioretention area are 4.6 meters (15 feet) wide by 12.2 meters (40 feet) in length. The minimum width allows enough space for a dense, randomly-distributed area of trees and shrubs to become established that replicates a natural forest and creates a microclimate. This enables the bioretention area to tolerate the effects of heat stress, acid rain, runoff pollutants, and insect and disease infestations which landscaped areas in urban settings typically are unable to tolerate. The preferred width is 7.6 meters (25 feet), with a length of twice the width. Any facilities wider than 6.1 meters (20 feet) should be twice as long as they are wide. This length requirement promotes the distribution of flow and decreases the chances of concentrated flow.

The maximum recommended ponding depth of the bioretention area is 15 centimeters (6 inches). This



BIORETENTION AREA
SIZING COMPUTATION

DEVELOPMENT	AREA SQ. FT.	"C" FACTOR	C X AREA
PAVEMENT	23,800	0.90	21,400
GRASS	10,100	0.25	2,500
TOTALS	33,900		23,900

BIOTENTION AREA SIZE

1. **With Sand Bed (5% Sum of C x Area)**
   = 05 x 23,900 = 1,195 OR SAY 1,200 sq. ft.
2. **Without Sand Bed (7% Sum of C x Area)**
   = 07 x 23,900 = 1,1673 OR SAY 1,700 sq. ft.

*** SEE CHAPTER IV. PRINCE GEORGES COUNTYSTORMWATER MANAGEMENT MANUAL**

Source: PGDER, 1993.

FIGURE 2 BIORETENTION AREA SIZING

depth provides for adequate storage and prevents water from standing for excessive periods of time. Because of some plants' water intolerance, water left to stand for longer than four days restricts the type of plants that can be used. Further, mosquitoes and other insects may start to breed if water is standing for longer than four days.

The appropriate planting soil should be backfilled into the excavated bioretention area. Planting soils should be sandy loam, loamy sand, or loam texture with a clay content ranging from 10 to 25 percent. The soil should have infiltration rates greater than 1.25 centimeters (0.5 inches) per hour, which is typical of sandy loams, loamy sands, or loams. Silt loams and clay loams generally have rates of less than 0.68 centimeters (0.27 inches) per hour. The pH of the soil should be between 5.5 and 6.5. Within this pH range, pollutants (e.g., organic nitrogen and phosphorus) can be adsorbed by the soil and microbial activity can flourish. Other requirements for the planting soil are a 1.5 to 3 percent organic content and a maximum 500 ppm concentration of soluble salts. In addition, criteria for magnesium, phosphorus, and potassium are 39.2 kilograms per acre (35 pounds per acre), 112 kilograms per acre (100 pounds per acre), and 95.2 kilograms per acre (85 pounds per acre), respectively. Soil tests should be performed for every 382 cubic meters (500 cubic yards) of planting soil, with the exception of pH and organic content tests, which are required only once per bioretention area.

Planting soil should be 10.1 centimeters (4 inches) deeper than the bottom of the largest root ball and 1.2 meters (4 feet) altogether. This depth will provide adequate soil for the plants' root systems to become established and prevent plant damage due to severe wind. A soil depth of 1.2 meters (4 feet) also provides adequate moisture capacity. To obtain the recommended depth, most sites will require excavation. Planting soil depths of greater than 1.2 meters (4 feet) may require additional construction practices (e.g., shoring measures). Planting soil should be placed in 18 inches or greater lifts and lightly compacted until the desired depth is reached. The bioretention area should be vegetated to resemble a terrestrial forest community ecosystem, which is dominated by understory trees (high canopy trees may be destroyed during maintenance) and has discrete soil zones as well as a mature canopy and a distinct sub-canopy of understory trees, a shrub layer, and herbaceous ground covers. Three species each of both trees and shrubs are recommended to be planted at a rate of 2500 trees and shrubs per hectare (1000 per acre). For example, a 4.6 meter (15 foot) by 12.2 meter (40 foot) bioretention area (55.75 square meters or 600 square feet) would require 14 trees and shrubs. The shrub-to-tree ratio should be 2:1 to 3:1. On average, the trees should be spaced 3.65 meters (12 feet) apart and the shrubs should be spaced 2.4 meters (8 feet) apart. In the metropolitan Washington, D.C., area, trees and shrubs should be planted from mid-March through the end of June or from mid-September through mid-November. Planting periods in other areas of the U.S. will vary. Vegetation should be watered at the end of each day for fourteen days following its planting.

Native species that are tolerant to pollutant loads and varying wet and dry conditions should be used in the bioretention area. These species can be determined from several published sources, including *Native Trees, Shrubs, and Vines for Urban and Rural America* (Hightshoe, 1988). The designer should assess aesthetics, site layout, and maintenance requirements when selecting plant species. Adjacent non-native invasive species should be identified and the designer should take measures (e.g., provide a soil breach) to eliminate the threat of these species invading the bioretention area. Regional landscaping manuals should be consulted to ensure that the planting of the bioretention area meets the landscaping requirements established by the local authorities.

The optimal placement of vegetation within the bioretention area should be evaluated by the designers. Plants should be placed at irregular intervals to replicate a natural forest. Shade and shelter from the wind will be provided to the bioretention area if the designer places the trees on the perimeter of the area. Trees and shrubs can be sheltered from damaging flows if they are placed away from the path of the incoming runoff. Species that are more tolerant to cold winds (e.g., evergreens) should be placed in windier areas of the site.

After the trees and shrubs are placed, the ground cover and/or mulch should be established. Ground cover such as grasses or legumes can be planted during the spring of the year. Mulch should be placed immediately after trees and shrubs are planted. Five to 7.6 cm (2 to 3 inches) of commercially-available fine shredded hardwood mulch or shredded hardwood chips should be applied to the bioretention area to protect from erosion. Mulch depths should be kept below 7.6 centimeters (3 inches) because more would interfere with the cycling of carbon dioxide and oxygen between the soil and the atmosphere. The mulch should be aged for at least six months (one year is optimal), and applied uniformly over the site.

PERFORMANCE

Bioretention removes storm water pollutants through physical and biological processes, including adsorption, filtration, plant uptake, microbial activity, decomposition, sedimentation and volatilization. Adsorption is the process whereby particulate pollutants attach to soil (e.g., clay) or vegetation surfaces. Adequate contact time between the surface and pollutant must be provided for in the design of the system for this removal process to occur. Therefore, the infiltration rate of the soils must not exceed those specified in the design criteria or pollutant removal may decrease. Pollutants removed by adsorption include metals, phosphorus, and some hydrocarbons. Filtration occurs as runoff passes through the bioretention area media, such as the sand bed, ground cover and planting soil. The media trap particulate matter and allow water to pass through. The filtering effectiveness of the bioretention area may decrease over time. Common particulates removed from storm water include particulate organic matter, phosphorus, and suspended solids. Biological processes that occur in wetlands result in pollutant uptake by plants and microorganisms in the soil. Plant growth is sustained by the uptake of nutrients from the soils, with woody plants locking up these nutrients through the seasons. Microbial activity within the soil also contributes to the removal of nitrogen and organic matter. Nitrogen is removed by nitrifying and denitrifying bacteria, while aerobic bacteria are responsible for the decomposition of the organic matter (e.g., petroleum). Microbial processes require oxygen and can result in depleted oxygen levels if the bioretention area is not adequately aerated.

Sedimentation occurs in the swale or ponding area as the velocity slows and solids fall out of suspension.

Volatilization also plays a role in pollutant removal. Pollutants such as oils and hydrocarbons can be removed from the wetland via evaporation or by aerosol formation under windy conditions. The removal effectiveness of bioretention has been studied during field and laboratory studies conducted by the University of Maryland (Davis et al, 1998). During these experiments, synthetic storm water runoff was pumped through several laboratory and field bioretention areas to simulate typical storm events in Prince George's County, MD. Removal rates for heavy metals an nutrients are shown in Table 1. As shown, the BMP removed between 93 and 98 percent of metals, between 68 and 80 percent of TKN and between 70 and 83 percent of total phosphorus. For all of the pollutants analyzed, results of the laboratory study were similar to those of field experiments. Doubling or halving the influent pollutant levels had little effect on the effluent pollutants levels (Davis et al, 1998). For other parameters, results from the performance studies for infiltration BMPs, which are similar to bioretention, can be used to estimate bioretention's performance. These removal rates are also shown in Table 1. As shown, the BMP could potentially achieve greater than 90 percent removal rates for total suspended solids, organics, and bacteria. The microbial activity and plant uptake occurring in the bioretention area will likely result in higher removal rates than those determined for infiltration BMPs.

TABLE 1 LABORATORY AND ESTIMATED BIORETENTION

Pollutant	Removal Rate
Total Phosphorus	70%-83% [1]
Metals (Cu, Zn, Pb)	93%-98% [1]
TKN	68%-80% [1]
Total Suspended Solids	90% [2]
Organics	90% [2]
Bacteria	90% [2]

Source: [1]Davis et al. (1998)
[2]PGDER (1993)

OPERATION AND MAINTENANCE

Recommended maintenance for a bioretention area includes inspection and repair or replacement of the treatment area components. Trees and shrubs should be inspected twice per year to evaluate their health and remove any dead or severely diseased vegetation. Diseased vegetation should be treated as necessary using preventative and low-toxic measures to the extent possible. Pruning and weeding may also be necessary to maintain the treatment area's appearance. Mulch replacement is recommended when erosion is evident or when the site begins to look unattractive. Spot mulching may be adequate when there are random void areas; however, once every two to three years the entire area may require mulch replacement. This should be done during the spring. The old mulch should be removed before the new mulch is distributed. Old mulch should be disposed of properly.

The application of an alkaline product, such as limestone, is recommended one to two times per year to counteract soil acidity resulting from slightly acidic precipitation and runoff. Before the limestone is applied, the soils and organic layer should be tested to determine the pH and therefore the quantity of limestone required. When levels of pollutants reach toxic levels which impair plant growth and the effectiveness of the BMP, soil replacement may be required (PGDER, 1993).

COSTS

Construction cost estimates for a bioretention area are slightly greater than those for the required landscaping for a new development. Recently-constructed 37.16 square meter (400 square foot) bioretention areas in Prince George's County, MD cost approximately $500. These units are rather small and their cost is low. The cost estimate includes the cost for excavating 0.6 to 1 meters (2 to 3 feet) and vegetating the site with 1 to 2 trees and 3 to 5 shrubs. The estimate does not include the cost for the planting soil, which increases the cost for a bioretention area. Retrofitting a site typically costs more, averaging $6,500 per bioretention area. The higher costs are attributed to the demolition of existing concrete, asphalt, and existing structures and the replacement of fill material with planting soil. The costs of retrofitting a commercial site in Maryland (Kettering Development) with 15 bioretention areas were estimated at $111,600.

The use of bioretention can decrease the cost for storm water conveyance systems at a site. A medical office building in Maryland was able to reduce the required amount of storm drain pipe from 243.8 meters (800 feet) to 70.1 meters (230 feet) with the use of bioretention. The drainage pipe costs were reduced by $24,000, or 50 percent of the total drainage cost for the site (PGDER, 1993). Landscaping costs that would be required at a development regardless of the installation of the bioretention area should also be considered when determining the net cost of the BMP.

The operation and maintenance costs for a bioretention facility will be comparable to those of typical landscaping required for a site. Costs beyond the normal landscaping fees will include the cost for testing the soils and may include costs for a sand bed and planting soil.

REFERENCES

1. Bitter, S., and J. Keith Bowers, 1994. Bioretention as a Water Quality Best Management Practice. *Watershed Protection Techniques*, Vol. 1, No.3. Silver Spring, MD.

2. Davis, A.P., Shokouhian, M., Sharma, H., and Minani, C., 1998. *Optimization of Bioretention Design for Water Quality and Hydrologic Characteristics*.

3. Hightshoe, G.L., 1988. *Native Trees, Shrubs, and Vines for Urban and Rural America.* Van Nostrand Reinhold, New York, New York.

4. Prince George's County Department of Environmental Resources (PGDER), 1993. *Design Manual for Use of Bioretention in Storm water Management*. Division of Environmental Management, Watershed Protection Branch. Landover, MD.

5. Prince George's County Department of Environmental Resources (PGDER), 1997. *Bioretention Monitoring: Preliminary Data Analysis*. Division of Environmental Management, Watershed Protection Branch. Landover, MD.

6. Reed, P.B., Jr, 1988. *National List of Species That Occur in Wetlands: Northeast*. United States Fish and Wildlife Service, St. Petersburg, Florida.

7. Schueler, T.R., 1987. *Controlling Urban Runoff: A Practical Manual for Planning*

and Designing Urban Best Management Practices. Metropolitan Washington Council of Governments.

8. Schueler, T.R., 1992. *A Current Assessment of Urban Best Management Practices.* Metropolitan Washington Council of Governments.

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Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring

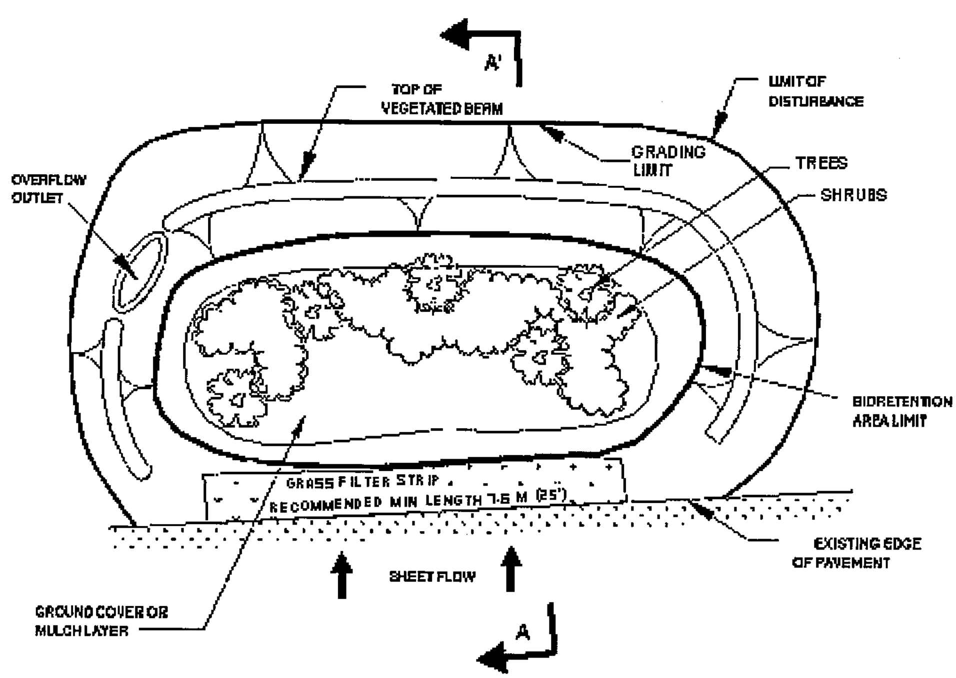
Fact Sheet - Bioretention

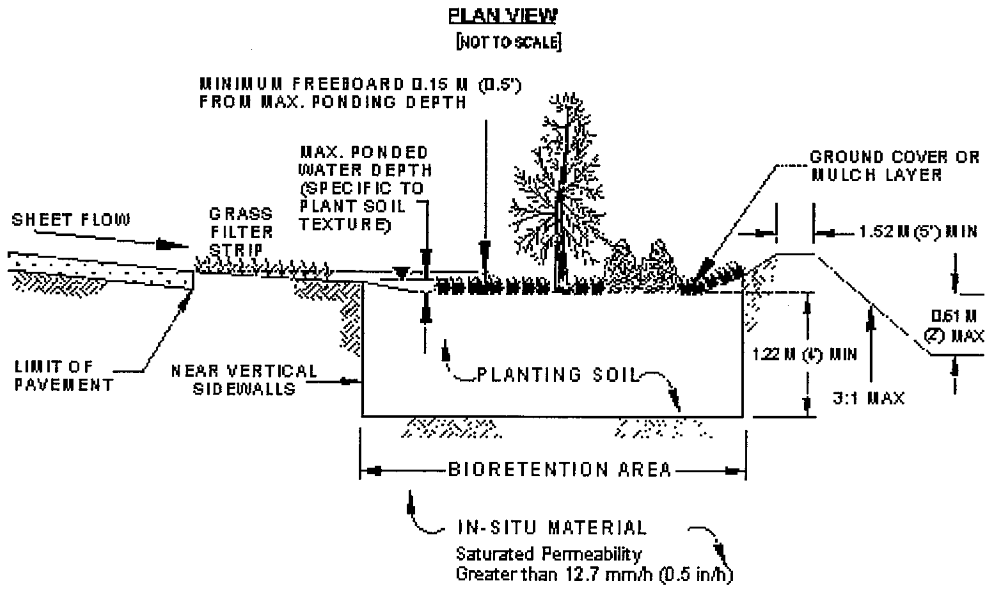
Bioretention was developed as an innovative approach in the ultra-urban environment. Bioretention areas (BAs) are easy to construct and require less infrastructure maintenance than many other BMPs. In addition to their well-accepted aesthetic value, BAs can be tailored in design and location to fit into the ultra-urban landscape.

Water quality improvements result from sedimentation, filtration, soil adsorption, microbial decay processes, and the uptake of pollutants by plants. The use of vegetation in BAs is modeled from the properties of a terrestrial forest community-an ecosystem dominated by mature trees, subcanopy of understory trees, shrubs, and herbaceous plants. Plants are selected based on their tolerance to varying hydrologic conditions, soil and pH requirements, and general characteristics like aesthetics. An additional important feature of bioretention is the soil in the system, which contains a mixture of detritus, humus, and mineral and biological complexes. The soil layer and the microbes living in the soil enhance infiltration, groundwater recharge, and nitrogen and metals removal; provide valuable water and nutrients for plant growth; and provide oxygen for plant root metabolism and growth.

BAs consist of a flow-regulating structure that processes inflow passing through a shallow depressed planted area containing ground cover (low-lying plant growth or an organic mulch), a planting soil supporting a range of facultative plant types, and a bottom support soil layer. Each of these features has a specific role in stormwater pollutant removal (Figure 6).

Figure 6. Parking edge and perimeter without curb (Prince George's County, Maryland, 1993)





Applicability

BAs have unique features that make them attractive for use in the ultra-urban environment. They have the ability to fit in existing or proposed medians or grassy areas along streets and parking lots. In addition, by disposing of a significant volume of annual rainfall on-site, BAs may reduce the infrastructure costs required to collect and convey the runoff off-site. BAs can also provide benefits other than stormwater management, including creating green areas and natural habitat. For facilities placed in new developments, the land area requirement and cost can be minimized if the local jurisdiction considers BAs part of the required vegetated open space set-aside or if installed trees count against local landscaping and tree coverage requirements.

Effectiveness

Limited monitoring of the effectiveness of BAs has been completed to date although there are ongoing monitoring efforts. Due to the similarity between bioretention technology and dry swales, however, the pollutant removal capability should be comparable (Claytor and Schueler, 1996). For planning purposes it is acceptable to anticipate BAs will remove 50 percent of total phosphorus (TP), 50 percent of total nitrogen (TN), between 75 and 80 percent of metals, and 75 percent of total suspended solids (TSS). Based on the nature of the planting soil and the facultative plants normally installed, BAs should be capable of managing some petroleum hydrocarbon concentrations commonly encountered in urban settings. Pretreatment is not considered crucial to the removal performance of BAs except where there is an atypically high level of pollutant loading, which can harm the planted growth (i.e., heavy commercial or industrial settings).

In variable climates, seasonal differences in removal performance should be anticipated for BAs, due to the growing and dormant periods of plants. Fall and winter temperatures force vegetation into dormancy, thereby reducing uptake of some runoff pollutants. However, carefully selected planting soil should provide significant storage capacity for many common urban pollutants during no/slow growth periods as long as soil infiltration can occur. Freezing temperatures greatly reduce infiltration in BAs and inactivate the most important pollutant removal mechanism.

BAs are intended to be water quality control practices, but they can be employed as either an on-line or off-line design. If BAs are employed as on-line facilities, design features must be incorporated to ensure nonerosive flow velocities exist within the BA. During these larger rainfall events, BAs should provide marginal treatment of the high flow volume (principally large-diameter suspended solids) even though the residence time in most facilities will be short.

Siting and Design Considerations

Bioretention is a relatively new technology being refined to achieve maximum water quality benefits. The basic design elements and major components of BAs are discussed below. For design examples and additional information, several good sources are available, including Design Manual for Use of Bioretention in Stormwater Management (Prince George's County, 1993), Design of Stormwater Filtering Systems (Claytor and Schueler, 1996), and Highway Runoff Manual (WSDOT, 1995).

The basic design elements to be addressed are proper soils, vegetation, and drainage. For most ultra-urban applications designers should look for relatively flat areas where deep soils (1.68 m [6 ft] to bedrock) are present and where seasonal high groundwater elevations are at least 1.68 m (6 ft) below grade. Ideally, BAs will discharge collected stormwater into underlying in situ soils and then into the surficial groundwater aquifer. As an option, designers can employ an underdrain system to collect exfiltration from the BA wherever existing deep soil layers will prevent exfiltration. Underdrains are typically placed approximately 1.52 m (5 ft) below grade and must drain by gravity to either an outlet or a storm drain. Underdrain systems can also be used in BAs where they will be placed in close proximity of building foundations. A minimum 9.2 m (30 ft) offset is recommended for BAs without underdrains.

Bioretention facilities combine a number of physical, biological, and hydrologic components to provide complementary functions to improve water quality, control hydrology, and provide wildlife and aesthetic improvements. The major components of the BA are:

- Pretreatment area (optional).
- Ponding area.
- Ground cover layer.
- Planting soil.
- In-situ soil.
- Plant material.
- Inlet and outlet controls.

Pretreatment Area

Some BA designs incorporate an upstream pretreatment area. Pretreatment is necessary where a significant volume of debris or suspended material will be conveyed by stormwater into the BA; for example, parking lots or commercial areas that are regularly sanded. In Figure 6, a grass buffer strip is used to reduce the runoff velocity and to filter large-diameter particulates from the runoff. Other pretreatment devices that can be employed are oil/grit separators, forebays, and stilling basins.

Ponding Area

In BAs the ponding area is located over the planting soil and provides surface storage for stormwater runoff while it infiltrates and/or evaporates after the rainfall period. Major design parameters for the ponding area are the maximum ponding depth and the duration of ponding. In Prince George's County, Maryland, these parameters were established based on the type of planting soil used and the type of adjacent land use. The higher the infiltration rate of the planting soil, the greater the maximum ponding depth (up to 0.3 m [12 in]). Applications in residential areas are permitted ponding for less than 24 hours; all other applications are permitted 36 hours of ponding (Prince George's County, Maryland, 1993).

Ground Cover Layer

The surface of the BA is covered with an organic ground cover layer. The organic layer provides a medium for biological growth and provides the carbon source needed for biological activities at the air/soil interface. It also helps to maintain a sufficient organic percentage in the surface soil horizon, in a sense simulating the leaf litter in forest communities. It is recommended that designers of BAs either use a mature mulch (maximum depth of 76.2 mm [3 in]) or establish permanent growth (e.g., grasses) within one growing season (Prince George's County, Maryland, 1993).

Planting Soil

BAs contain a thick layer of planting soil, located below the ground cover layer and supported by the underlying in situ soils. This thickness also provides for deep root plant growth. Planting soil must have a high infiltration rate, support healthy plant growth, adsorb nutrients and pollutants, and provide additional storage capacity for stormwater. These objectives can be met by using a planting soil containing a clay content of 2.5 to 10 percent and an organic content between 1.5 and 3 percent.

Prince George's County permits BAs with higher infiltration soils to have a greater ponding depth, which resulted in a smaller surface area of the BA. Based on this approach, designers might have to choose between using less expensive existing onsite soils or replacing existing soils with imported highly permeable soils to permit a smaller BA. To provide the infiltration necessary to remove ponded stormwater it is recommended that the soil texture be sand, loamy sand, sandy loam, loam, or silt loam. In addition it is recommended that the planting soil thickness be 1.22 m (4 ft) to ensure significant contact time between infiltrating stormwater and the soil. This soil depth will also help deeply rooted plant growth become well established (Prince George's County, Maryland, 1993).

In Situ Soil

As shown in Figure 6, the in situ soil layer provides a foundation for planting soils and drains the infiltrated stormwater from BAs. Experimental BAs have shown that in situ soils are crucial to the success of the facility; if a location drains in a poor manner, the

BA will fail unless another means of drainage is established. Prince George's County, Maryland, recommended percolation tests be performed to demonstrate that in situ soils possess at least 12.7 mm/h (0.5 in/h) infiltration capacity. Where poorly drained in situ soils are encountered, it is still feasible to install bioretention but only with the aid of an underdrain system. Additional information on investigating in situ soils and designing underdrain systems is provided in the Prince George's County Design Manual for Use of Bioretention in Stormwater Management (Prince George's County, Maryland, 1993).

Plant Material

The role of plant species is to use nutrients and other pollutants and remove water from the planting soil through evapotranspiration. Plants must be a low-maintenance, aesthetically pleasing variety that is tolerant of urban stormwater pollutants. They must have the ability to adapt to conditions of drought and inundation. Key design parameters for optimum plant material function include species diversity, density, and morphology, and the use of native plants. Ideally, the community structure will be similar to that of a forest community, providing diversity to reduce susceptibility to insect and disease infestation. The intention is to create a microclimate that is resistant to urban stresses. The plants selected must be able to prosper even when flooded to a depth of 0.15 m (0.5 ft) or more at frequent intervals.

Inlet and Outlet Controls

The specifics of inlets and outlets of BAs are highly dependent on whether the BA is an on-line or off-line design. An on-line facility is one that does not have a bypass that diverts excess stormwater around the BA once it becomes full.

Because all stormwater will pass through an on-line bioretention facility, both inlets and outlets must be designed to ensure that the runoff rate does not damage the BA. Prince George's County states that designers must ensure nonerosive flow velocities exist within the BA for the 10-year postdevelopment event (Prince George's County, Maryland, 1993). On-line facility designs usually include protection such as riprapped inlets and outlets, which are designed through an in-depth hydraulic evaluation. Possible outlets for on-line areas include drop inlets or overflow weirs that feed downstream swales or pipe systems.

Off-line BAs generally require smaller inlets than on-line facilities because inlets are usually designed to convey the runoff from the first 12.7 mm (0.5 in) of runoff from the site. All other runoff must be diverted around the BA and downstream to subsequent swales or pipe systems without passing through the BA. This diversion can be established by creating a ponding area in the BA, which causes backwater conditions and a resulting shift in discharge direction.

Designers must be careful not to undersize entrances into BAs and to keep entrance velocities in excess of 0.15 m/s (0.5 ft/s) to help prevent clogging of the inlet area. Debris (e.g., sand) on the parking area can be washed toward the bioretention inlet and form a small dike, blocking the inlet.

Maintenance Considerations

BAs require routine, low-cost maintenance, similar to conventional landscaping maintenance, to ensure the system functions well as a stormwater BMP and remains aesthetically pleasing. Routine inspections of the bioretention facility, semiannually for the first year and annually thereafter, along with spot inspections after major storms the first year to verify the BA has not been significantly disturbed, aid in ensuring the performance of the BA. Other maintenance considerations include:

- Planting soil bed - check the pH of the soils, correct erosion, cultivate unvegetated areas to reduce clogging from fine sediments over time.
- Ground cover layer - mulch or replant bare spots annually.
- Planting materials - replace dead or severely distressed vegetation, perform periodic pruning, etc.
- Inflow/outflow - inspect for clogging, remove sediment build-up, repair eroded pretreatment areas, remove accumulated trash and debris.

Cost Considerations

Initial estimates from engineers designing BAs suggest project costs will be approximately $24,700 per impervious hectare ($10,000 per impervious acre), exclusive of real estate costs (Bell, 1996).

References

Bell, W. 1996. BMP Technologies for Ultra-Urban Settings. In Proceedings of Effective Land Management for Reduced Environmental Impact, Tidewater's Land Management Conference on Water Quality, August 22, 1996.

Claytor, R.A., and T.R. Schueler. 1996. Design of Stormwater Filtering Systems. The Center for Watershed Protection, Silver Spring, MD.

Prince George's County. 1993. Design Manual for Use of Bioretention in Stormwater Management. Department of Environmental Resources, Prince George's County, Landover, MD.

Washington State Department of Transportation (WSDOT). 1995. Highway Runoff Manual. Washington State Department of Transportation.

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Low Impact Development Center, Inc.

Tree Box Filter

Tree box filters are mini bioretention areas installed beneath trees that can be very effective at controlling runoff, especially when distributed throughout the site.[1] Runoff is directed to the tree box, where it is cleaned by vegetation and soil before entering a catch basin. The runoff collected in the tree-boxes helps irrigate the trees.

DISCLAIMER

BUILD IT!

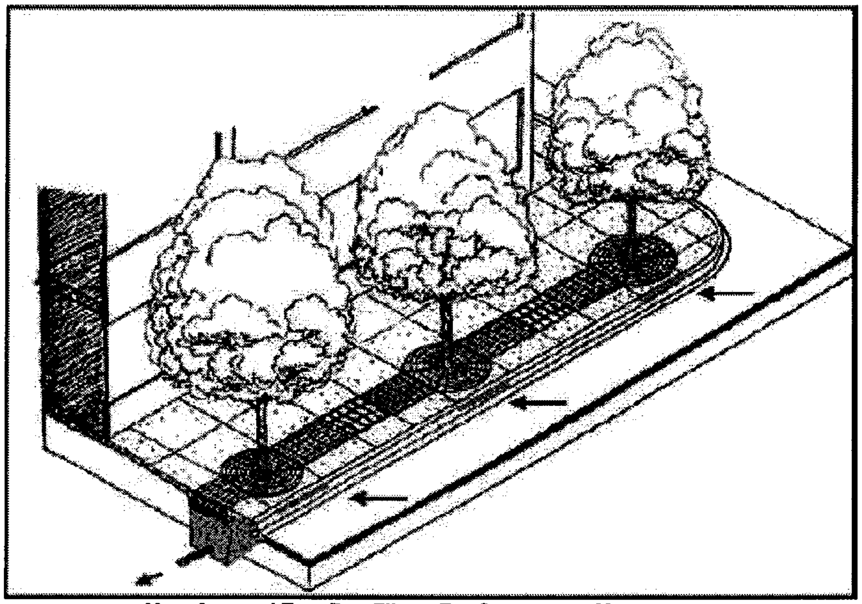
AUTOCAD #1
AUTOCAD #2
AUTOCAD #3
AUTOCAD #4
AUTOCAD #5
JPEG #1
JPEG #2
JPEG #3
JPEG #4
JPEG #5
SPECIFICATIONS
SIZING

RELATED INFO

COSTS
MAINTENANCE

WHY?

BENEFITS



Manufactured Tree Box Filters For Stormwater Management
(Source: Virginia DCR Stormwater Management Program)

Tree box filters are based on an effective and widely used "bioretention or rain garden" technology with improvements to enhance pollutant removal, increase performance reliability, increase ease of construction, reduce maintenance costs and improve aesthetics. Typical landscape plants (shrubs, ornamental grasses, trees and flowers) are used as an integral part of the bioretention / filtration system. They can fit into any landscape scheme increasing the quality of life in urban areas by adding beauty, habitat value, and reducing urban heat island effects.

The system consists of a container filled with a soil mixture, a mulch layer, under-drain system and a shrub or tree. Stormwater runoff drains directly from impervious surfaces through a filter media. Treated water flows out of the system through an under drain connected to a storm drainpipe / inlet or into the surrounding soil. Tree box filters can also be used to control runoff volumes / flows by adding storage volume beneath the filter box with an outlet control device.

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[1] Natural Resources Defense Council, 2001: *Stormwater Strategies: Community Responses to Runoff Pollution.*
http://www.nrdc.org/water/pollution/storm/stoinx.asp

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Appendix 2

Bioretention Design Examples

The following examples, from different locations in the U.S., illustrate a variety of concepts and specifications useful for developing bioretention facilities specific to local needs.

1. Bioretention Cell: Prince George's County, Maryland

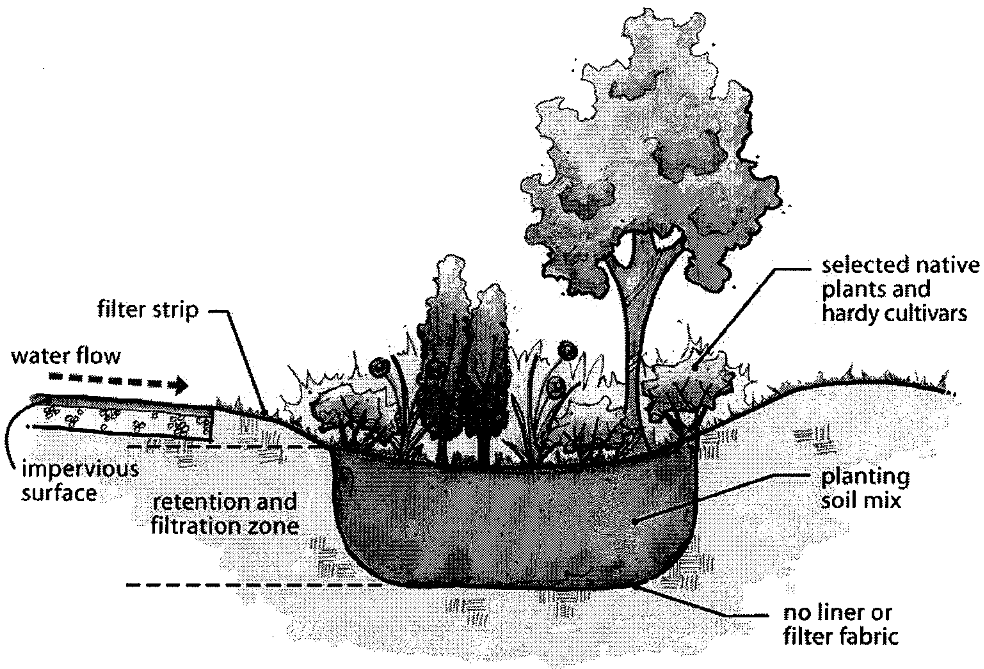

Figure 1 Typical bioretention design section.
Graphic by AHBL Engineering

Type of facility

- General application for infiltration and recharge, not recommended for contaminant hotspots.
- The initial bioretention design applied in the U.S. and the most simple design type.

Contributing area: 1-acre maximum with a maximum of ½-acre impervious area recommended.

Sizing: modified TR 55.

Flow path: off-line preferred, in-line permitted.

Planting soil depth: 2.5 feet minimum—allows for adequate filtration above native soil.

Soil:

Native soil (outside of excavated area)

- Minimum infiltration rate of 1 inch/hour.

Planting soil mix

- 50 to 60% sand, 20 to 30% leaf compost, and 20 to 30% topsoil.
- Infiltration rate not reported; however, recommended porosity for soil mix is approximately 25%.
- Topsoil is sandy loam, loamy sand or loam texture (USDA texture triangle).
- Maximum clay content < 5%.
- pH range 5.5 to 6.5.
- Uniform mix free of stones, stumps, roots or other similar material > 2 inches.
- Clean sand (0.02 to 0.04 inches) meeting AASHTO M-6 or ASTM C-33.

Comments

This is the initial planting soil specification developed for bioretention areas in the early 1990s and has been successfully applied in facilities operating for the past 10 years.

Pretreatment: provide grass or vegetated strip if space allows.

Under-drain: none

Gravel blanket: none

Filter fabric: none unless placed along sides to reduce lateral flows under adjacent pavement areas (e.g. median strip or parking lot island).

Mulch:

- 3-inch maximum, well-aged (12 months min.) shredded hardwood (shredded minimizes floating of material during surface water ponding), use fresh bark mulch when additional nitrogen retention desirable.

Compaction:

- Place soil in lifts of 12 to 18 inches.
- Do not use heavy equipment in bioretention basin.
- If compaction occurs at bottom of facility during excavation, rip to a minimum 12 inches and till 2 to 3 inches of sand into base before backfilling.
- If final grading of soil mix cannot be accomplished by hand, use light, low ground-contact pressure equipment.

Surface pool dewater: 3 to 4 hours.

System dewater: less than 48 hours.

Max ponding depth: 6 inches.

(Prince George's County, 2002)

2. Bioretention cell: Prince George's County, Maryland

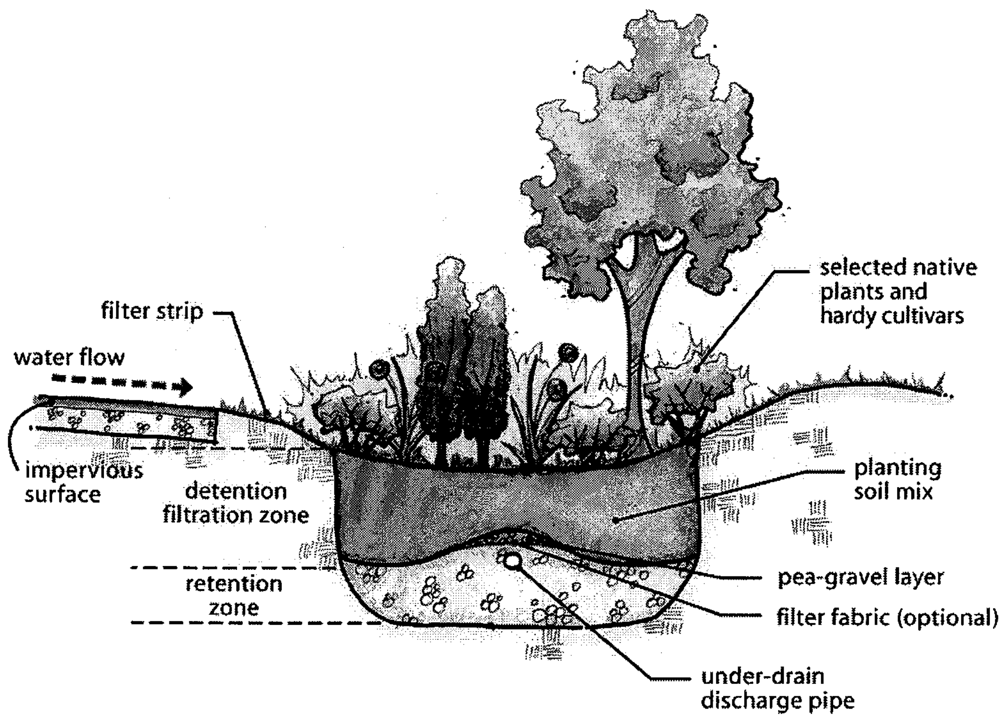

Figure 2 Bioretention design with elevated under-drain and fluctuating aerobic/anaerobic zone.
Graphic by AHBL Engineering

Type of facility:

- General application for infiltration, filtration, and recharge where high nitrogen loadings are anticipated.
- Design allows for a fluctuating aerobic/anaerobic zone below the raised under-drain discharge pipe.
- Design can be used for contaminant hotspot areas with liner.

Contributing area: 2-acre maximum with a maximum of 1-acre impervious area recommended.

Sizing: modified TR 55.

Flow path: off-line preferred, in-line permitted.

Planting soil depth: 2.5 feet minimum

Soil:

Native soil (outside of excavated area)

- Minimum infiltration rate can be less than 1 inch/hour with under-drain.

Planting soil (see Example #1)

Pretreatment: provide grass or vegetated strip if space allows.

Under-drain:

- 6 to 8-inch diameter rigid schedule 40, ½-inch perforations, 6 inches center to center.

Gravel blanket:

- Under-drain gravel bed: ½ to 1½-inch diameter washed stone AASHTO M-43.
- Pea gravel diaphragm (placed between planting soil and drain rock for improved sediment filtration): ¼ to ½-inch diameter washed stone ASTM D 448, 3 to 8 inches thick.

Filter fabric:

- Non-woven ASTM D-4491, permittivity 75 gal/min/ft^2 minimum, installed horizontally on top of the drain rock extending 1 to 2 feet either side of under-drain pipe located below.
- Filter fabric on bottom or sides of facility is not recommended unless used to restrict lateral or vertical flow.
- If pea gravel diaphragm is used, filter fabric can be placed between drain rock and diaphragm to impede direct gravitational flow.

Mulch:

- 3-inch maximum, well-aged (12 months min.) shredded hardwood (shredded minimizes floating of material during surface water ponding), use fresh bark mulch when additional nitrogen retention desirable.

Surface pool dewater: 3 to 4 hours.

System dewater: less than 48 hours.

Max ponding depth: 6 inches.

(Prince George's County, 2002)

3. Bioretention Swale: Seattle Public Utilities (SEA Street project)

Figure 3 SEA Street bioretention swale. *Photo by Colleen Owen*

Type of facility: Redesign of 660-foot existing street using bioretention swales within right-of-way for infiltration and conveyance.

Construction date: 1999 to 2000.

Contributing area: 2.3 acres (approximately 35% total impervious area).

Sizing: Santa Barbara Unit Hydrograph.

Flow path: in-line.

Planting soil depth: approximately 1 foot.

Soil:

Native soil

- Heterogeneous till-like material (not true lodgement till) with lens of silt, sand, and gravel material of varying permeability.

Planting soil

- Bottom of swales: 50% approved native soil and 50% decomposed organic compost by volume, thoroughly mixed. Remaining areas: 70 to 75% approved native soil and 25 to 30% compost by volume, thoroughly mixed.
- Infiltration rate not reported.

Comments

This soil specification has proven successful for infiltration requirements and plant growth and health at the SEA Street project; however, Seattle has modified the specification as noted in the Broadview Green Grid project (see example #4).

Pretreatment: none.

Under-drain:

- 6- to 8-inch slotted PVC pipe with surface drains set at designed flow depth elevations, solid iron pipe under driveways.
- Ultimate outfall to existing roadside ditch at end of block.
- Some areas lined with clay to restrict infiltration and possible subsurface flow to residential basements.

Gravel blanket: Seattle type 26 (sand gravel mix, see Section 6.1.2.3 Bioretention components for specification).

Filter fabric: none.

Mulch: 3-inch depth minimum (same as compost used for soil mix).

Compaction:

- No heavy equipment allowed in bioretention swale area during construction.
- No excavation during wet or saturated conditions.
- Soil installed in maximum lifts of 6 inches and foot compacted.

Surface pool dewater: not available.

System dewater: not available.

Max ponding depth: Live storage: 12 inches. Dead storage: 0 inches.

(Tackett, 2004; Seattle Public Utilities, 2000; personal communication, Tracy Tackett 2004)

4. Bioretention Swale: Seattle Public Utilities (Broadview Green Grid project)

Figure 4 Broadview green grid bioretention swale. *Photo courtesy of Seattle Public Utilities.*

Type of facility: Redesign of existing streets using bioretention swales within right-of-way for infiltration and conveyance (several blocks in length).

Construction date: 2003 to 2004.

Facility depth: 1 to 2.5 feet.

Contributing area: 2.9 to 3.7 acres (34 to 42% TIA) plus 32 acres (34% TIA) east-west streets. North-south street shown in Figure 4.

Sizing: XP-WSM

Flow path: in-line.

Soil:

Native soil (outside excavation area)

- C soils (SCS)

Planting soil mix

- Three different soil mixes are used in the Broadview Green Grid project depending on required infiltration rate, load bearing, and timing of installation.

1. Engineered Soil Mix

The Engineered Soil Mix is used in bioretention swale areas where higher infiltration rates and additional detention is desired. This mix is also used in road shoulder areas adjacent to bioretention/swales and is expected to maintain relatively good infiltration rates at 85% to 90% compaction.

- Design infiltration rate: 2 inches/hour.

Soil mix:

- 65% to 70% gravelly sand and 30% to 35% compost (see specification below).
- Gravelly sand gradation per ASTM D 422:

Sieve size	Percent Passing
2-inch	100
¾-inch	70-100
¼-inch	50-80
US No. 40	15-40
US No. 200	0-3

- The soil mixture should be uniform, free of stones, stumps, roots or other similar objects larger than 2 inches.
- On-site soil mixing or placement not allowed if soil is saturated or subject to water within 48 hours.
- Cover and store soil accordingly to prevent wetting or saturation.
- Test soil for fertility and micronutrients and, if necessary, amend mixture to create optimum conditions for plant establishment and early growth at rates recommended by an independent laboratory soil test.
- Place soil in lifts not exceeding 6 inches.

Comments

This soil specification maintains a higher infiltration rate at typical compaction rates. While the city of Seattle anticipates good performance from this specification, the mix may be slightly less optimum for plant growth than bioretention soil mixes 1 and 2 (see specification below) and has not been tested long-term for plant health performance.

2. Bioretention Soil Mix 1

Bioretention Soil Mix 1 uses on-site excavated soil mixed with compost.

Design infiltration rate: 0.3 to 1.0 inch/hour (varies with properties of native soils).

Soil mix:

- Approximately 65% approved on-site soil and 35% compost material thoroughly mixed.
- Excavated soil for mixing should be free of large woody debris or garbage (concrete or asphalt chunks, old pipe, etc.).
- Collect and test representative samples of excavated soil for gradation.
- Using on-site excavated soil is not appropriate for on-site soils with high clay content. The excavated soil should be sandy loam, loamy sand or loam texture (USDA texture triangle). The excavated soil can be amended with appropriate aggregate (e.g. sand) to achieve the appropriate texture.
- Cover and store soil accordingly to prevent wetting or saturation.
- Test soil for fertility and micronutrients and, if necessary, amend mixture to create optimum conditions for plant establishment and early growth at rates recommended by an independent laboratory soil test.
- Organic content of the soil mixture should be 8% to 12%.

Comments

On-site excavated soil, rather than imported soil, is specified as part of an overall sustainability strategy for Seattle. Using on-site excavated soil for the amended soil mix may reduce control over gradation, organic content, and final product performance, can increase project costs, and can complicate construction logistics when attempting to blend soil mix components in restricted space (personal communication, Tracy Tackett, 2004).

3. Bioretention Soil Mix 2

Bioretention Soil Mix 2 is mixed off-site and delivered ready for installation.

Design infiltration rate: 1 inch/hour.

Soil mix:

- 65% to 70% gravelly sand and 30% to 35% compost (see specification below).
- Gravelly sand gradation per ASTM D 422.

Sieve size	Percent Passing
US No. 4	100
US No. 6	88-100
US No. 8	79-97
US No. 50	11-35
US No. 200	5-15

- Maximum clay content should be less than 5%.
- Soil mixture should be uniform, free of stones, stumps, roots or other similar objects larger than 2 inches.
- On-site soil mixing or placement not allowed if soil is saturated or subjected to water within 48 hours.
- Cover and store soil accordingly to prevent wetting or saturation.
- Test soil for fertility and micronutrients and, if necessary, amend mixture to create optimum conditions for plant establishment and early growth at rates recommended by an independent laboratory soil test.
- Organic content of the soil mixture should be 8% to 12%.

Comments

The city of Seattle uses soil mix 2 during the wet season when maintaining dry native soil for mixing on-site is difficult. Bioretention soil mix 2 is a "vegetable garden mix" supplied by Cedar Grove Composting of Washington.

Compost material (for all 3 soil mixes)

- Material must be in compliance with WAC chapter 173-350 section 220 and meet Type 1, 2, 3 or 4 feedstock.
- See Section 6.2: Amending Construction Site Soils for compost specification.

Pretreatment: none.

Under-drain:

- 6 to 8-inch slotted PVC pipe, solid iron pipe under driveways.
- Under-drains connected to next downstream swale.

Gravel blanket: Seattle type 26 (sand gravel mix, see Section 6.1: Bioretention Areas for specification).

Filter fabric: none.

Mulch: 3-inch depth minimum. Compost used for mulch in bottom of swale and shredded tree trimmings in surrounding areas.

Compaction:

- No heavy equipment allowed in bioretention/swale area during construction.
- No excavation during wet or saturated conditions.
- Soil installed in maximum lifts of 6 inches and foot compacted.

Surface pool dewater: 24 hours.

System dewater: not reported.

Max ponding depth: 12 inches (total live and dead storage).

(Tackett, 2004; personal communication Tracy Tackett, 2004)

5. Sloped Bio*detention*: Austin, Texas

Figure 5 This sloped biodetention facility was a more cost-effective design for an Austin, Texas subdivision than a conventional pond. *Photo courtesy of Murphee Engineering.*

Type of facility: sloped biodetention using grassy vegetative barriers (hedgerows) on contour to detain storm flows and reduce pollutant loads.

Contributing area: not known.

Flow path: in-line.

Planting soil depth: 12-inch deep by 8-inch wide trenches excavated for planting vegetated barriers.

Soil:

Native soil

- C and D soils (SCS) on Karst formations.
- Infiltration rate not reported.

Planting soil:

- Native soil with slow release fertilizer.
- Infiltration rate not reported.

Pretreatment: rock berm used as a level spreader to distribute and release flow across slope and vegetative barriers down slope.

Under-drain: none.

Gravel blanket: not applicable.

Filter fabric: none.

Mulch: none.

Hedge plantings:

- Alamo switchgrass (*Panicum zizanioides*) in 8-inch wide rows on contour.
- Species should be adapted to local soil and climate conditions, easily established, long-lived, as well as have stiff stems that remain erect through the year. Grass species that can emerge through sediment deposits and resume growth from buried stem nodes, rhizomatous or stoloniferous growth habit are desired (Natural Resources Conservation Service, 2001).
- First row receiving discharges is double planted (one row a few inches down slope of the first row) using 4-inch slips on 4-inch centers.
- Planted at 110 stems per square foot.
- Area between hedgerows planted in grass for slope and soil stability and additional filtering.

Spacing: 25 feet between hedgerows (2 to 2.5% slope). Spacing will depend on slope.

Sizing and Hedgerow length:

- 2-year design storm (2.64 inches/3 hours) used for sizing.
- Hedgerows designed to manage 0.2 cfs discharge from contributing area per foot of hedgerow.

(Murphee, Scaief and Whelan, 1997)

United States
Environmental Protection Agency

Office of Water (4203)
Washington, DC 20460

EPA-841-B-00-005A
October 2000

Bioretention Applications

Inglewood Demonstration Project, Largo, Maryland
Florida Aquarium, Tampa, Florida

Key Concepts:

- Retrofits
- Structural Controls
- Source Controls

LOW-IMPACT DEVELOPMENT CENTER

Introduction

Two case studies demonstrate the potential to use integrated management plans (IMPs) in the design of new parking facilities and as retrofits for existing parking facilities. The Inglewood study in Largo, Maryland, compared the pollutant removal efficiency of a bioretention cell in a laboratory setting to that of a comparable facility constructed in a parking lot. The Florida Aquarium study in Tampa, Florida, included monitoring of several storm events for volume and water quality control.

Inglewood Project Area

The project area is an existing 5-acre outdoor parking area located in a highly urbanized office park adjacent to Interstate 95. Runoff from adjacent areas does not flow across the lot. The slope of the parking area is approximately 3 percent. Parking stalls are aligned at 90-degree angles, and there are approximately 30 cars in each row of an aisle. At the end of each aisle are planting areas surrounded by curbs and gutters. Curb drainage inlets have been placed in some of the islands to intercept and collect runoff as sheet flow, which is piped to a downstream regional stormwater management facility.

Inglewood Project Description

The Inglewood project consisted of a laboratory segment and a field segment. The laboratory segment involved construction of a planter box filled with a typical bioretention facility soil mixture (50 percent construction sand, 20 to 30 percent topsoil, and 20 to 30 percent compost). This facility is approximately half the size in volume of the Inglewood facility. The box was planted with representative plants and mulched. A synthetic stormwater mixture was applied and the pollutant removal efficiency, temperature, and runoff volume rate were measured. The pollutant

Project Benefits:

- Retrofit Opportunity
- Pollutant Removal
- Volume Reduction
- Cost-Effectiveness

mix included metals (copper, lead, and zinc), phosphorus, organic nitrogen, and nitrate.

A landscaped island measuring approximately 38 feet by 12 feet was chosen as the retrofit area. The island contains a curb inlet that drains into the municipal storm drain system. Almost the entire drainage area is impervious. A 4-foot slot was cut into the curb immediately before the inlet. The landscaped island was then excavated to a depth of 4 feet. An underdrain was installed and tied into the bottom of the existing inlet to completely drain the planting soil to avoid oversaturation. The underdrain was covered with 8 inches of 1- to 2-inch gravel and backfilled with typical bioretention soil mix. The backfill extended to a depth of about 12 inches below the top of the curb, which allows for a ponding depth of approximately 6 inches of water in the island

Figure 1. Bioretention landscaping at the Inglewood demonstration project site.

Table 1. Summary of bioretention pollutant removal results for the Inglewood demonstration project.

Pollutant	Input mean ± standard deviation	Output mean ± standard deviation	Output range	Output percent removal mean ± standard deviation
Cu dissolved (μg/L)	120 ± 27	63 ± 6.5	55–75	48 ± 12
Cu total (μg/L)	120 ± 27	69 ± 9.4	55–85	43 ± 11
Pb dissolved (μg/L)	54 ± 9.4	11 ± 6	6.7–25	79 ± 26
Pb total (μg/L)	54 ± 9.4	16 ± 7	6.7–26	70 ± 23
Zn dissolved (mg/L)	1.1 ± 0.021	0.24 ± 0.44	0.11–0.56	78 ± 29
Zn total (mg/L)	1.1 ± 0.021	0.39 ± 0.44	0.12–1.4	64 ± 42
Ca (mg/L)	44 ± 6.4	32 ± 6.1	24–41	27 ± 14
Cl^- (mg/L)	5.1 ± 0.48	162 ± 80	74–228	3,000[a]
Na (mg/L)	3.1	359 ± 170	68–497	11,000[a]
P (mg/L)	0.83	0.11 ± 0.017	0.10–0.13	87 ± 2
TKN (mg/L as N)	6.9 ± 0.81	2.3 ± 0.64	1.7–3.0	67 ± 9
NO_3^- (mg/L as N)	1.3 ± 0.05	1.1 ± 0.15	0.94–1.2	15 ± 12

[a]Shows percent production.

before a backwater is created at the curb opening. Subsequently the area was planted and covered with 3 inches of shredded hardwood mulch. Figure 1 shows the bioretention area after vegetation was established.

The stormwater mixture was applied to a 50-square-foot area in the field facility at a rate of 1.6 inches per hour for 6 hours. The removal rates for several pollutants are shown in Table 1. In addition to pollutant removal, the runoff temperature was lowered approximately 12 °C as the runoff was processed and filtered through the soil mixture. Most of the pollutant removal process occurred in the mulch layer.

A similar field investigation was conducted on an 8-year-old facility, and the metals removal rate was much higher (Davis et al., 1998). This effect might be attributed to slower flow rates through the soil, which has higher clay content, as well as greater pollutant uptake by vegetation.

Inglewood Project Summary and Benefits

This study showed the feasibility of retrofitting an existing parking facility and demonstrated the consistency of laboratory and field pollutant removal performance. The retrofit cost approximately $4,500 to construct and treats approximately one-half acre of impervious surface. The bioretention retrofit was a more cost-effective way to filter pollutants than many proprietary devices designed to treat the same volume of runoff. These proprietary devices could cost $15,000 to $20,000, would be more expensive to maintain, and would not significantly decrease runoff volume or temperature. Also, bioretention areas offer the ancillary benefit of aesthetic enhancement. It is interesting to note that a drought occurred after the installation of the plants, and although many of the other plants in the parking lot died or experienced severe drought stress, the plants in the bioretention facility survived because of the retained water supply.

Florida Aquarium Project Area

The Florida Aquarium site is an 11.5-acre, asphalt and concrete parking area that serves approximately 700,000 visitors per year. Runoff was controlled using the following IMPs:

- End-of-island bioretention cells
- Bioretention swales located around the parking perimeter
- Permeable paving
- Bioretention strips between parking stalls
- A small pond to supplement storage and pollutant removal

Figure 2 is an illustration of the site that details the type and location of runoff controls.

Florida Aquarium Project Description

A total of 30 storm events were monitored for one year at the Florida Aquarium site during 1998-1999. The Southwest Florida Water Management

District measured rainfall and flow from eight of the subcatchments in the parking area and collected water quality samples on a flow-weighted basis. Comparisons between pavement areas controlled by IMPs and uncontrolled asphalt areas were made for peak runoff rate, runoff volume, runoff coefficients, and water quality. Sediment cores from swales also were collected and analyzed.

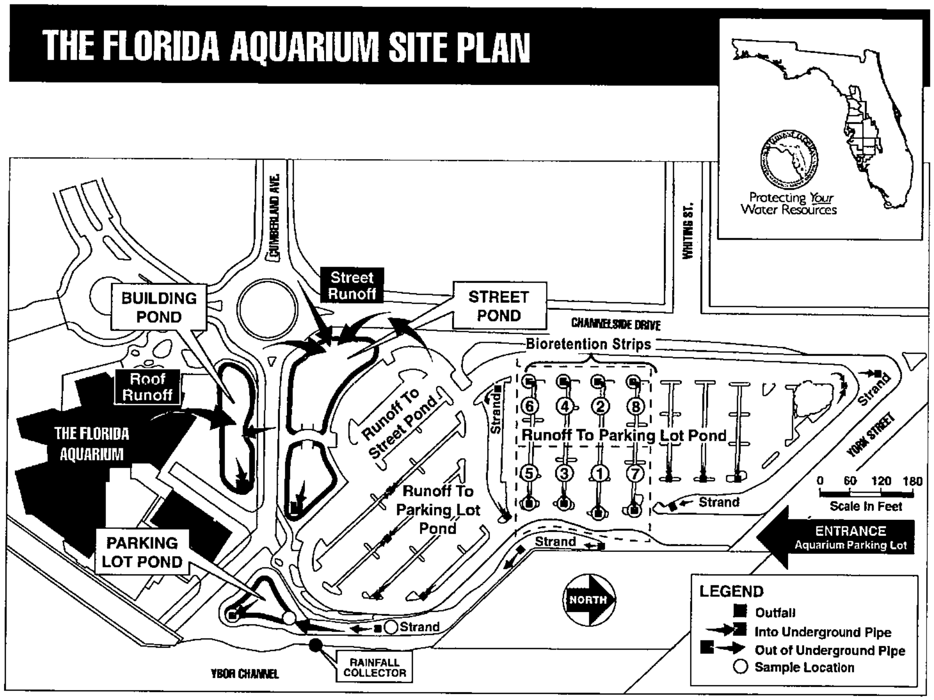

Figure 2. Layout of the Florida Aquarium site with IMPs. The eight basins outlined with dotted lines were evaluated in this part of the study.

Florida Aquarium Project Summary and Benefits

The parking areas controlled by IMPs showed a significant reduction in runoff volume and peak runoff rate. Table 2 shows pollutant load reductions for three pavement types; reduction is compared to pollutant loads in runoff from a basin without a swale. Much of the pollutant reduction is attributed to the reduced runoff in basins with swales. Because the swales are only the first element in the treatment train, even better removal efficiencies should be seen when data are analyzed for the entire system.

Table 2. Load efficiency of pollutants expressed as percent reduction for three types of pavement at the Florida Aquarium site.

Constituents	Percent pollutant reduction[a]		
	Asphalt w/swale	Cement w/swale	Porous w/swale
Ammonia	45	73	85
Nitrate	44	41	66
Total Nitrogen	9	16	42
Orthophosphorus	-180	-180	-74
Total Phosphorus	-94	-62	3
Suspended Solids	46	78	91
Copper	23	72	81
Iron	52	84	92
Lead	59	78	85
Manganese	40	68	92
Zinc	46	62	75

[a]The basins with swales were compared to a basin without a swale to determine the amount of reduction in pollutant loads possible using these small alterations. Notice that the efficiencies for phosphorus are negative, indicating an increase in phosphorus load in the basins with a swale.

References

Davis, A., M. Shokouhian, H. Sharma, and C. Minami, 1998. *Optimization of Bioretention Design for Water Quality and Hydrologic Characteristics*. Report 01-04-31032. Final report to Prince George's County, Maryland.

Rushton, B. 1999. *Low Impact Parking Lot Design Reduces Runoff and Pollutant Loads: Annual Report #1*. Southwest Florida Watershed Management District, Brooksville, Florida.

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Soil Enhancement/Amendment

The following excerpt is from http://www.lid-stormwater.net/soilamend/soilamend_home.htm
The reader is further referred to Chollak, T. and P. Rosenfeld, 1998: Guidelines For Landscaping with Compost-Amended Soils. University of Washington College of Forest Resources to obtain Washington-specific guidance.

Site preparation prior to the construction of residential units typically involves removing or stock piling the existing vegetation and topsoil. This has an immediate hydrologic impact because of the reduction in soil structure, pore space, organic content and biological activity. After construction, a thin layer of topsoil is usually spread on the now very compacted subsoil and then the area is seeded or sodded.

Magnified view of native soil
(Source: King County DNR Solid Waste Division)

Magnified view of disturbed soil
(Source: King County DNR Solid Waste Division)

The combination of soil compaction and loss of organic matter has several undesirable consequences:

- With the infiltration capacity of the site significantly reduced, rainwater more quickly runs off into local streams. This, in turn, tends to increase erosion, scouring and the sediment load.
- The rate of groundwater recharge decreases.
- Due to the soil compaction and the loss of organic matter, the availability of subsurface water to plants is reduced.
- The increased volume and frequency of runoff carries pollutants with it that include pesticides, fertilizers, animal wastes and chemicals such as phosphorous and nitrogen.
- Homeowners now have to apply pesticides, fertilizers and irrigation water in increasing amounts in order to maintain their landscapes. [1]

Soil additives, or amendments, can be used to minimize development impacts on native soils by restoring their infiltration capacity and chemical characteristics. After soils have been amended their improved physical, biological and hydrological characteristics will make them more effective agents of stormwater management.

Soil Amendment Component Properties / Quantities

Soil amendments can include not only compost and mulch but also top soil, lime and gypsum. These additional components help offset any nutritional deficiencies and control acidity.

A thorough soil analysis of the native soil is required to determine the optimum quantity for each component in order to obtain the maximum benefit from compost amending. Soil amendment components should generally be mixed and applied in the following manner. [2]

Uniform mixing of compost using a rototiller
(Source: US Composting Council)

- *Compost.* The amount of compost to be applied depends upon the organic content of the existing soil as well as the targeted amount of the proposed soil amendment. Compost typically has an organic content of 45-60% and is often used as the sole means of providing organic material to the soil profile. In soils that have organic contents of less than one percent, 8 to 13 percent by soil weight is a typical target of a proposed soil amendment with compost. As a general rule, a 2-to-1 ratio of existing soil to compost, by loose volume, will achieve the desired organics level. Locally available compost may be utilized if it is of high enough quality and available at a cost effective price.

- *Nutrients and Lime.* If the soil pH is below 6.0 the addition of pelletized dolomite is recommended, with application rates in the range of 50 to 100 pounds per 1000 square feet. Nitrogen requirements usually range from 2 to 8 pounds per 1000 square feet, with slow release water-insoluble forms being the preferred method. Other soil additions may include sulfur and boron with the amount needed determined by soil analysis.

- *Gypsum*. Hydrated calcium sulfate ($CaSO_4 \bullet 2H_2O$) is sometimes applied to a soil in order to increase calcium and sulfur without affecting the pH, as well as to enhance a soil's structure in high clay content soils.

1

Documents:

Soils for Salmon, 1999: The Relationship Between Soil and Water, How Soil Amendments and Compost Can aid in Salmon Recovery.

Chollak, T. and P. Rosenfeld, 1998: Guidelines For Landscaping with Compost-Amended Soils. University of Washington College of Forest Resources. . Available from http://www.ci.redmond.wa.us/insidecityhall/publicworks/environment/pdfs/compostamendedsoils.pdf

Stenn, Howard, 2003. Guidelines and Resources for Implementing Soil Depth & Quality BMP T.5.13 in WDOE Western Washington Stormwater Manual. See www.soilsforsalmon.org or http://compostwashington.org/PDF/SOIL_MANUAL.pdf

Soils for Salmon: Integrating Stormwater, Water Supply and Solid Waste Issues in New Development and Existing Landscapes

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The Soils for Salmon initiative, a cooperative effort of agencies around the region, addresses the fundamental problem of the loss of soil functions as we turn native forests into cities and towns. Stormwater detention is one of those critical soil functions, but they also include soil structure (which affects the need for irrigation and chemical inputs in landscapes) nutrient and organic "waste" recycling (i.e. fertility), plant disease protection, and biofiltration of urban pollutants. These are the functions of living, biologically and organically rich soils. While nothing can fully restore the functions provided under native forest conditions, a soil protection and soil restoration strategy will be essential to reducing the impacts of development in this region.

In new development, best management practices include retaining and reusing native soil and vegetation, reducing the construction footprint and minimizing soil compaction, and restoring function in disturbed soils by amending them with compost. Existing landscapes can be retrofitted by tilling in compost and using organic mulches. These practices have multiple benefits, and are cost-effective in terms of improved plant vigor and reduced need for water, fertilizer, and pesticides, as well as enhanced stormwater detention and water quality.

Why a Soil Strategy is Essential: The Connection Between Soil and Water

In native forests in the Puget Sound region, 50% of the rain that falls returns to the sky through evapotranspiration, to fall again as rain further inland. 35% or more is infiltrated into groundwater and the rest is detained in interflow through the upper soil layers.[1] Almost none runs off the surface. This function of soils and forest reduces damaging winter storm flow peaks, while recharging groundwater to provide "base flows" of cool water to streams in the summer.

By comparison, in developed suburban areas, where soils have been stripped and compacted and most of the forest has been removed, less than 30% of rainfall is returned to the sky through evapotranspiration, and less than 16% is detained and infiltrated into groundwater. Impervious surfaces like roads and roofs of course detain none at all. The result is extremely fast runoff during storms, which erodes surface soil and stream banks, carries urban pollutants into streams, scours salmon redds and other aquatic life, and leaves spawning gravels choked with sediment. Groundwater is not recharged, so that summer base flows are reduced, leaving streams shallower and warmer. Stormwater detention structure regulations to date have reduced, but not prevented this damage.[1] Studies in this region show that the first 5-10% of constructed impervious area in a watershed, under current practices, results in significant damage to its ability to support native aquatic life, including salmon.[2]

Forests and native topsoils, and thus their stormwater management functions, are disappearing in the Puget Sound region. In a satellite photo analysis, between 1972 and 1996 the amount of land with more than 50% tree cover decreased by 37% (from 42% of land down to 27%).[3] Meanwhile population in

Puget Sound doubled between 1962 and 1998, and continues to rise. The Census Bureau estimates that by 2020 Washington will add 2.7 million new residents, the equivalent of 5 new cities the size of Seattle, or 14 new Spokanes. We need a strategy to protect native soil function wherever possible during development, restore soil function on sites disturbed during development, and retrofit soils in existing urban areas.

Restoring Soil Function with Organic Amendments

Stormwater and erosion management One way to restore some of the forest's functions in urbanized areas is to restore soils by incorporating plenty of compost or other organic matter (2-4 inches of compost tilled into the upper 8-12 inches of soil, depending on soil type). One study demonstrated up to 50% reduction in winter storm runoff from plots of glacial till soil amended with compost, as compared to un-amended till soil.[4] Compost amendment works well with the glacial till, clay, sand or gravel soils common in developing areas of this region. Compost blankets on steep slopes and compost berms in place of silt fences have also proven capable of controlling short term erosion, while enhancing long term revegetation and slope stability.[5]

Added benefits Compost-amended soils also filter out urban pollutants such as hydrocarbons and heavy metals from cars, and pesticides or soluble fertilizers applied to landscapes, keeping them from reaching streams. By improving soil fertility and plant resistance, compost greatly reduces the need for pesticides and synthetic fertilizers, thus potentially further reducing nonpoint water pollution. Recycling of municipal yard and food waste, biosolids, construction and landclearing debris, and agricultural wastes into beneficial soil amendments reduces the demand for landfill space and reduces nutrient runoff to streams. And by improving soil moisture retention and plant rooting depth, compost greatly reduces summer irrigation needs, reducing peak demand on strained regional water supplies and allowing us to leave more water in rivers for fish.

Restoring soil life How does compost improve soil structure, fertility, bio-filtration and plant vigor? By providing food and homes for the incredibly diverse web of tiny creatures that make up the soil ecosystem. These organisms aggregate soil particles to create soil structure and pore spaces from the micro up to the macro scale. They break down organic pollutants and bind heavy metals. They recycle nutrients endlessly and make them available to plants. And they compete with and parasitize the pests and diseases that attack plants, creating naturally healthier more attractive landscapes that are easier to maintain.[6]

organic matter + soil organisms + time ⇒ soil structure, fertility, bio-filtration, & stormwater detention

A cost-effective solution for new development For developers and landscape contractors, amending soils before planting results in much better plant survival, growth rates, disease and pest resistance, and thus better long term appearance and fewer callbacks, improving the bottom line. For homeowners, proper soil amendment reduces landscape maintenance needs and can pay for itself in the first few years based on water and chemical savings alone, not counting the value of stormwater and pollution reduction benefits.[7]

Improving soil function in existing development On existing sites, soils should be amended with compost when re-landscaping. Trees, especially native conifers, can be added wherever possible. Buffers of native plants can be planted adjacent to waterways. And existing landscapes can be mulched with organic mulches like wood chips, bark, leaves, grass clippings and compost on an annual basis to significantly improve soil function. Lawn areas can be topdressed with compost and shifted to ecologically sound turf management practices that enhance soil life and thus soil functions.[8]

Summary of Soils Best Management Practices

New Construction BMP's

- Retain and protect native topsoil & vegetation (esp. trees!)
- Minimize construction footprint
- Store and reuse topsoil from site
- Retain "buffer" vegetation along waterways
- Restore disturbed soils by tilling 2-4" of compost into upper 8-12" of soil (or deeper) before planting. (Use a tractor-mounted ripper to loosen compacted layers within 12" of surface.)

Existing Landscape BMP's

- Retrofit soils by tilling in compost when re-landscaping
- Mulch beds with organic mulches (leaves, wood chips, compost), and topdress turf with compost
- Avoid overuse of soluble chemical fertilizers and pesticides, which may damage soil life

Taking it to the Streets: Implementing a Soil Strategy Around the Region

Beginning in March 1999, the Washington Organic Recycling Council and member public agencies have sponsored Soils for Salmon seminars, conference presentations, and policy and education initiatives to raise awareness of the need for a soils strategy among policy makers and stormwater and development professionals. Progress includes:

- **Policy and Regulation** Soils BMP's have been included in the draft Washington State Dept. of Ecology Stormwater Management Manual, draft Puget Sound Water Quality Action Team Management Plan, and Seattle's Stormwater Manual. King County's draft Site Alterations ordinance revision would require restoration of soil functions in new development. The Tri-County (Snohomish, King and Pierce) Stormwater plan and the National Marine Fisheries Service Citizen's Guide to the 4(d) Rule both include soil amendment guidelines.
- **Public and Professional Education** King County and Seattle have developed extensive new public outreach on soils, composting, and natural landscaping practices. Professional education seminars have reached landscape contractors, developers, architects, and public agency staff. The Master Builders Association of King and Snohomish Counties includes soil strategies in it's new "Built Green" Sustainable Building initiative.
- **Technical Standards** Snohomish County, where this initiative began, is sponsoring development of science-based soil amendment specifications and inspection standards, which will be applicable around the region. This work builds on research initiated by the City of Redmond and the University of Washington, among others. Research and specifications testing is also under way in Clark County, a City of Tacoma/Washington State University project, and a Portland Metro/Oregon DEQ project.
- **Implementation** One site where soil amendment is working is at new Redmond Ridge development in King County, a large planned community where forest has been retained where possible, and all disturbed soils have been amended to a 12 inch depth, primarily with duff and organics recycled from site clearing. Another is the S.E.A. Streets demonstration project in Seattle, where a residential street retrofit includes soil amendment, detention swales, and native/low water use landscaping. The WA State Department of Transportation now uses organic amendments widely in road landscaping and in slope erosion control.

Challenges for the Future

Soil protection and restoration are clearly an essential part of Low Impact Development strategies for the Puget Sound region. Needed steps toward implementing this strategy include:

- Development of standard specifications and inspection procedures for soil amendment (which is under way in the Snohomish Soil Improvement project).
- Research and field tests of appropriate amounts and types of amendment for different soil types.
- Quantification of the improvement in stormwater detention on different soil types.
- Widespread implementation on various sites, and reporting in case studies from those sites to build the practical knowledge base.
- Further adoption and testing of model soil protection/restoration regulations.
- Continuing outreach to the development community and stormwater management professionals.

References

[1] Beyerlein, Douglas, and Joseph Brascher. "Traditional Alternatives: Will More Detention Work?" in *Salmon in the City*, proceedings of conference in Mt. Vernon, WA, 1998, pp. 45-48. Copies available by calling WA State Univ. (253) 445-4575, or download under "Links" at the web site http://www.depts.washington.edu/cuwrm/

[2] Horner, Richard R., and Christopher W. May. "Watershed Urbanization and the Decline of Salmon in Puget Sound Streams" in *Salmon in the City* conference proceedings, 1998, pp. 19-40. See source above.

[3] Smith, Dan. "The Case for Greener Cities." *American Forests*, Vol. 105, No. 3, Autumn 1999, pp. 34-39. <u>and</u> Moll, Gary. "Trees are Money." *Imaging Notes*, Vol. 14, No. 1, Jan/Feb 1999.

[4] Kolsti, Kyle F., Burges, Stephen J., and Bruce W. Jensen. *Hydrologic Response of Residential-Scale Lawns on Till Containing Various Amounts of Compost Amendment.* Univ. of WA Center for Urban Water Resources, for WA Dept. of Ecology, 1995, pp. 1,88. Copies available from UW Engineering Professional Programs at (206) 543-5539

[5] Tyler, Rod. "Compost Filter Berms and Blankets". *Biocycle*, vol. 42, No. 1, Jan. 2001, pp. 26-33

[6] Coleman, David C., and D. A. Crossley, Jr. *Fundamentals of Soil Ecology.* San Diego; Academic Press (Harcourt Brace & Company), 1996, pp. 12-167.

[7] Chollak, Tracy, and Paul Rosenfeld. *Guidelines for Landscaping with Compost-Amended Soils.* City of Redmond Public Works, 1998, p. I.1-I.4. Download from City of Redmond website at http://www.ci.redmond.wa.us/insidecityhall/publicworks/environment/education.asp <u>and</u> King County DNR/Cascadia Consulting, *Landscape Focus Group Findings: Compost Use.* Dec. 2000.

[8] McDonald, David K. *Ecologically Sound Lawn Care for the Pacific Northwest: Findings from the Scientific Literature and Recommendations from Turf Professionals.* City of Seattle Public Utilities, 1999, pp. 15-18. Download under "Research" at http://www.ci.seattle.wa.us/util/rescons or request copy at (206)684-7560.

Resources

Background Science

Proceedings of the 1998 *Salmon in the City* conference <u>http://depts.washington.edu/cuwrm/</u>

This is the UW Center for Urban Water Resources Management website. Look under "Links" to download the conference proceedings. This site also includes many other research papers on the effects of urbanization, stream restoration techniques, trials of permeable paving products, etc.

Soil Restoration and Compost Use

Washington Organic Recycling Council / Soils for Salmon <u>http://www.compostwashington.org/</u>

Complete background and up to date information on Soils for Salmon initiative, and useful links on compost use and soil restoration.

"The Relationship Between Soil and Water - How Soil Amendments and Compost Can Aid in Salmon Recovery" by Josh Marx, Andy Bary, Sego Jackson, David McDonald, and Holly Wescott, Seattle, 1999. This paper with useful graphics and a slide show are downloadable from the web site http://www.metrokc.gov/dnr/swd/ResRecy/soil4salmon.htm

WA Dept. of Ecology, Solid Waste & Compost http://www.ecy.wa.gov/programs/swfa/index.html
See the *Interim Guidelines for Compost Quality* at http://www.ecy.wa.gov/biblio/94038.html

U.S. Composting Council http://compostingcouncil.org/
The most authoritative source for information on compost specifications. Particularly useful to landscape professionals is the recently updated *Field Guide to Compost Use* which can be downloaded at http://compostingcouncil.org/FGCU.html

Penn State Turfgrass Extension http://www.agronomy.psu.edu/Extension/Turf/TurfExt.html
Download Dr. Peter Landschoot's practical guide, *Using Composts to Improve Turfgrass Performance*

Soil Biology and Soil Functions: Why Soil Life Matters

Soil Foodweb Inc. http://www.soilfoodweb.com/
Dr. Elaine Ingham's (of Oregon State University) site is the best place to start for information on soil organisms and their functions, soil biological analyses, compost tea, and more.

Idaho BLM "Soil Biological Communities" http://www.id.blm.gov/soils/index.html
Excellent microphotos of soil organisms and simple descriptions of the roles they play in maintaining soil structure & fertility and fighting plant disease.

US Dept. of Agriculture, NRCS Soil Quality Institute http://www.statlab.iastate.edu/survey/SQI/
Download the excellent *Soil Biology Primer*, or order print copies from 1-800-THE SOIL

For More Information Contact:

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www.compostwashington.org

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http://dnr.metrokc.gov/swd/resrecy/soil4salmon.htm

David McDonald, Seattle Public Utilities (206) 684-7650 david.mcdonald@ci.seattle.wa.us
http://www.ci.seattle.wa.us/util/rescons/

Holly Wescott, WA Dept. of Ecology (360) 407-6113 hwes461@ecy.wa.gov
http://www.ecy.wa.gov/programs/swfa/index.html

Composting Council of Oregon http://www.compostingcouncilofor.org/SfS/SfShome.html

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BMP T5.13 Post-Construction Soil Quality and Depth

Purpose and Definition

Naturally occurring (undisturbed) soil and vegetation provide important stormwater functions including: water infiltration; nutrient, sediment, and pollutant adsorption; sediment and pollutant biofiltration; water interflow storage and transmission; and pollutant decomposition. These functions are largely lost when development strips away native soil and vegetation and replaces it with minimal topsoil and sod. Not only are these important stormwater functions lost, but such landscapes themselves become pollution- generating pervious surfaces due to increased use of pesticides, fertilizers and other landscaping and household/industrial chemicals, the concentration of pet wastes, and pollutants that accompany roadside litter.

Establishing soil quality and depth regains greater stormwater functions in the post development landscape, provides increased treatment of pollutants and sediments that result from development and habitation, and minimizes the need for some landscaping chemicals, thus reducing pollution through prevention.

Applications and Limitations

Establishing a minimum soil quality and depth is not the same as preservation of naturally occurring soil and vegetation. It also does not maximize the stormwater functions that could be attained through greater soil depth and more specialized formulations as presented in BMP T5.35, Engineered Soil/Landscape Systems. However, establishing a minimum soil quality and depth will provide improved on-site management of stormwater flow and water quality.

Soil organic matter can be attained through numerous materials such as compost, composted woody material, biosolids, and forest product residuals. It is important that the materials used to meet the soil quality and depth BMP be appropriate and beneficial to the plant cover to be established. Likewise, it is important that imported topsoils improve soil conditions and do not have an excessive percent of clay fines.

Design Guidelines

- Soil retention. The duff layer and native topsoil should be retained in an undisturbed state to the maximum extent practicable. In any areas requiring grading remove and stockpile the duff layer and topsoil on site in a designated, controlled area, not adjacent to public resources and critical areas, to be reapplied to other portions of the site where feasible.

- Soil quality. All areas subject to clearing and grading that have not been covered by impervious surface, incorporated into a drainage facility or engineered as structural fill or slope shall, at project completion, demonstrate the following:

1. Retention or enhancement of the moisture infiltration rate and soil moisture holding capacity of the original undisturbed soil native to the site. Areas which have been compacted or have removed some or all of the duff layer or underlying top soil shall be amended to mitigate for lost moisture infiltration and moisture holding capacity; and
2. A topsoil layer with a minimum organic matter content of ten percent dry weight and a pH from 6.0 to 8.0 or matching the pH of the original undisturbed soil. The topsoil layer shall have a minimum depth of eight inches except where tree roots limit the depth of incorporation of amendments needed to meet the criteria. Subsoils below the topsoil layer should be scarified at least 4 inches with some incorporation of the upper material to avoid stratified layers, where feasible.

- These criteria can be met by using on-site native topsoil, incorporating amendments into on-site soil, or importing blended topsoil. If blended topsoil is imported, then fines should be limited to twenty-five percent passing through a 200 sieve.
- The resulting soil should be conducive to the type of vegetation to be established.

Maintenance

- Soil quality and depth should be established toward the end of construction and once established, should be protected from compaction, such as from large machinery use, and from erosion.
- Soil should be planted and mulched after installation.
- Plant debris or its equivalent should be left on the soil surface to replenish organic matter.
- It should be possible to reduce use of irrigation, fertilizers, herbicides and pesticides. These activities should be adjusted where possible, rather than continuing to implement formerly established practices.

BMP T5.35 Engineered Soil/Landscape Systems

Purpose and Definition

The engineered soil/landscape system is a self-sustaining soil and plant system that simultaneously supports plant growth, soil microbes, water infiltration, nutrient and pollutant adsorption, sediment and pollutant biofiltration, water interflow, and pollutant decomposition.

Applications and Limitations

Installing an engineered soil/landscape system is not the same as preservation of natural vegetation. However, it can provide improvements to both the post-development plant and soil systems and help them function more effectively. This provides a soil/landscape system with adequate depth, permeability, and organic matter to sustain itself by creating a sustainable nutrient cycle.

Amending existing landscapes and turf systems to improve depth, permeability, and percent organic matter can substantially improve the disease and drought resistance of the vegetation and reduce fertilizer demand. Organic matter is the least water-soluble form of nutrient that can be added to the soil. Composted organic matter generally releases only between 2 and 10 percent of its total nitrogen annually, and this release corresponds closely to many plant growth cycles. If natural plant debris and mulch are returned to the soil this system can continue regenerating natural nutrients indefinitely.

Landscaped areas are frequently used to treat and infiltrate runoff from adjacent impervious areas. They are also used in treatment BMPs for removal of pollutants, control of peak flows, and control of erosion. However, the standard modeling approach for hydrologic analysis and flow control prescribes that designers use only marginal values for lawns and landscaping. The best runoff performance allowed for lawns and landscapes is less than that of pasture, grasslands, and woods. Providing an engineered soil/landscape system allows the designer to use the landscape as a flow control system.

Design Guidelines

Provide an engineered soil/landscape system that has the following characteristics:

- Protected from compaction and erosion.
- A plant system (landscape design) to support a sustained soil quality.
- A soil depth that is equivalent to pasture and grassland in runoff curve numbers.

- Permeability characteristics of not less than 6.0, 2.0, 0.6, and less than 0.6 inches/hour for hydrologic soil groups A, B, C, and D, respectively (per ASTM D 3385).
- Minimum percent organic matter of 12, 14, 16, and 18 percent for hydrologic soil groups A, B, C, and D, respectively (per ASTM D 2974).

Maintenance

The system should be protected from compaction and erosion. Compaction should be prevented using BMP T5.36.

- The system should be planted or mulched after installation.
- Plant debris or its equivalent should be left on the soil surface.
- Pesticides and herbicides should be used infrequently or not at all.
- Fertilizer, if used, should be applied in the form of organic matter, organic-based, or in a slow-release, non-water soluble form.

BMP T5.36 Soil Compaction Protection and Mitigation

Purpose and Definition

Landscaped areas are frequently used to treat and infiltrate runoff from adjacent impervious areas. They are also used in treatment BMPs for removal of pollutants, control of peak flows, and control of erosion. Compaction and permeability are directly related. As landscapes mature, they often become more compact due to loss of organic matter, climate- and pathogen-related stress on landscape plantings, foot traffic, vehicle/mower pressures, turf thatching, and similar activities.

Provide protection from compaction through the use of amendments. These include, but are not limited to, organic matter, coarse sand, pumice, granulated rubber, and similar soil components. Also provide protection from compaction through appropriate landscape plant selection and placement, and by defining foot traffic and vehicle pathways.

Design Guidelines

- Compost (WSDOT standard specification 8-02, section 8-12.2 with supplement 02021.FR8) can be used to increase organic matter to the 12 to 18 percent range.
- Coarse sand and pumice can be added to improve permeability. Clay soils may respond differently than other soils. For clay soils, the organic matter should be added first, and then sand or pumice added as a final ingredient to prevent the creation of an impermeable, cement-like matrix.
- Lawns can be aerated and then top-dressed with appropriate amendments to improve permeability.
- Granulated (crumb) rubber has successfully been incorporated into lawns, golf courses (EPA Publication 530-F-97-043), and athletic fields to improve permeability and resistance to compaction where the surface has constant and heavy use.
- Landscapes that are designed to prevent excessive foot traffic and vehicle/mower compression can better retain their permeability.
- Landscapes should have well-defined pathways that are designed to withstand frequent or excessive foot traffic and vehicle compression.

Permeable Pavement

The following excerpt is from http://www.mapc.org/regional_planning/LID/permeable_paving.html

Overview:

Since impervious pavement is the primary source of stormwater runoff, Low Impact Development strategies recommend permeable paving for parking areas and other hard surfaces. Permeable paving allows rainwater to percolate through the paving and into the ground before it runs off. This approach reduces stormwater runoff volumes and minimizes the pollutants introduced into stormwater runoff from parking areas.

All permeable paving systems consist of a durable, load bearing, pervious surface overlying a crushed stone base that stores rainwater before it infiltrates into the underlying soil. Permeable paving techniques include porous asphalt, pervious concrete, paving stones, and manufactured “grass pavers” made of concrete or plastic. Permeable paving may be used for walkways, patios, plazas, driveways, parking stalls, and overflow parking areas.

Management Objectives

Reduce stormwater runoff volume from paved surfaces
Reduce peak discharge rates.
Increase recharge through infiltration.
Reduce pollutant transport through direct infiltration.
Improve site landscaping benefits (grass pavers only.)

Applications and Design Principles

Permeable paving is appropriate for pedestrian-only areas and for very low-volume, low-speed areas such as overflow parking areas, residential driveways, alleys, and parking stalls. It can be constructed where the underlying s oils have a permeability of at least 0.3” per hour. Permeable paving is an excellent technique for dense urban areas because it does not require any additional land. With proper design, cold climates are not a major limitation; porous pavement has been used successfully in Norway, incorporating design features to reduce frost heave.

Permeable paving is not ideal for high traffic/high speed areas because it has lower load-bearing capacity than conventional pavement. Nor should it be used on stormwater “hotspots” with high pollutant loads because stormwater cannot be pretreated prior to infiltration. Heavy winter sanding may clog joints and void spaces.

A schematic cross section of permeable paving. In some applications, the crushed stone reservoir below the paving is designed to store and infiltrate rooftop runoff as well. Image: Cahill Associates, Inc. 2004

There are three major types of permeable paving:

- Porous asphalt and pervious concrete appear to be the same as traditional asphalt or concrete pavement. However, they are mixed with a very low content of fine sand, so that they have 10%-25% void space and a runoff coefficient that is almost zero.
- Paving stones (aka unit pavers) are impermeable blocks made of brick, stone, or concrete, set on a prepared sand base. The joints between the blocks are filled with sand or stone dust to allow water to percolate downward. Runoff coefficients range

from 0.1 – 0.7, depending on rainfall intensity, joint width, and materials. Some concrete paving stones have an open cell design to increase permeability.

- Grass pavers (aka turf blocks) are a type of open-cell unit paver in which the cells are filled with soil and planted with turf. The pavers, made of concrete or synthetic, distribute the weight of traffic and prevent compression of the underlying soil. Runoff coefficients are similar to grass, 0.15 to 0.6.

Each of these techniques is constructed over a base course that doubles as a reservoir for the stormwater before it infiltrates into the subsoil. The reservoir should consist of uniformly-sized crushed stone, with a depth sufficient to store all of the rainfall from the design storm. The bottom of the stone reservoir should be completely flat so that infiltrated runoff will be able to infiltrate through the entire surface. Some designs incorporate an "overflow edge," which is a trench surrounding the edge of the pavement. The trench connects to the stone reservoir below the surface of the pavement and acts as a backup in case the surface clogs.

Benefits and Effectiveness

Porous pavement provides groundwater recharge and reduces stormwater runoff volume. Depending on design, paving material, soil type, and rainfall, permeable paving can infiltrate as much as 70% to 80% of annual rainfall.
Porous pavement can reduce peak discharge rates significantly by diverting stormwater into the ground and away from the pipe-and-pond stormwater management system.
Grass pavers can improve site appearance by providing vegetation where there would otherwise be only pavement.
Porous paving increases effective developable area on a site because portions of the stormwater management system are located underneath the paved areas, and the infiltration provided by permeable paving can significantly reduce the need for large stormwater management structures on a site.
Limitations

Permeable paving can be prone to clogging from sand and fine sediments that fill void spaces and the joints between pavers. As a result, it should be used carefully where frequent winter sanding is necessary because the sand may clog the surface of the material. Periodic maintenance is critical, and surfaces should be cleaned with a vacuum sweeper at least three times per year.
In cold climates, the potential for frost heave may be a concern for the use of permeable paving. Some design manuals recommend excavating the base course to below the frost line, but this may not be necessary in rapidly permeable soils. In addition, the dead air and void spaces in the base course provide insulation so that the frost line is closer to the surface.
Permeable paving should not receive stormwater from other drainage areas, especially any areas that are not fully stabilized.
Permeable paving can only be used on gentle slopes (<5%); it cannot be used in high-traffic areas or where it will be subject to heavy axle loads.
Snow plows can catch the edge of grass pavers and some paving stones. Rollers should be attached to the bottom edge of a snowplow to prevent this problem.

Maintenance

- Post signs identifying porous pavement areas.
- Minimize use of salt or sand during winter months
- Keep landscaped areas well-maintained and prevent soil from being transported onto the pavement.
- Clean the surface using vacuum sweeping machines monthly. For paving stones, periodically add joint material (sand) to replace material that has been transported.
- Monitor regularly to ensure that the paving surface drains properly after storms.

- Do not reseal or repave with impermeable materials.
- Inspect the surface annually for deterioration or spalling.
- Grass pavers may require periodic reseeding to fill in bare spots.

Cost:

On most sites, permeable paving costs more than conventional asphalt or cement paving techniques. In the case of porous asphalt and pervious concrete, construction costs may be 50% more than conventional asphalt and concrete. Construction costs of paving stones and grass pavers varies considerably and will depend on the application. As with any site improvement or stormwater management structure, property owners should provide a budget for maintenance of permeable paving, at an annual rate of 1%-2% of construction costs.

Permeable paving reduces the need for stormwater conveyances and treatment structures, resulting in cost savings elsewhere. Permeable paving also reduces the amount of land needed for stormwater management and may satisfy requirements for greenspace, allowing more development on a site.

Industry Websites:

Porous Asphalt
www.hotmix.org

Porous Concrete
www.lehighcement.com
www.washingtonconcrete.org
www.cadman.com

Unit Pavers
http://www.uni-groupusa.org/uni-eco-.htm
http://www.sspco.org/geoblock.html
http://www.invisiblestructures.com

Stormwater Management Fact Sheet: Porous Pavement

Description

Porous pavement is a permeable pavement surface with an underlying stone reservoir that temporarily stores surface runoff before infiltrating into the subsoil. This porous surface replaces traditional pavement, allowing parking lot runoff to infiltrate directly into the soil and receive water quality treatment. There are several pavement options, including porous asphalt, pervious concrete, and grass pavers. Porous asphalt and pervious concrete appear the same as traditional pavement from the surface, but are manufactured without "fine" materials, and incorporate void spaces to allow infiltration. Grass pavers are concrete interlocking blocks or synthetic fibrous grid systems with open areas designed to allow grass to grow within the void areas. Other alternative paving surfaces can help reduce the runoff from paved areas but do not incorporate the stone trench for temporary storage below the pavement (see the Green Parking Fact Sheet). While porous pavement has the potential to be a highly effective treatment practice, maintenance has been a concern in past applications of the practice.

Application

The ideal application for porous pavement is to treat a low traffic or overflow parking area. Porous pavement may also have some application on highways, where it is currently used as a surface material to reduce hydroplaning (see the Bridge and Roadway Maintenance Fact Sheet).

Regional Applicability

Porous pavement can be applied in most regions of the country, but the practice has unique challenges in cold climates. Porous pavement cannot be used where sand is applied to the pavement surface because the sand will clog the surface of the material. Care also needs to be taken when applying salt to a porous pavement surface since chlorides from road salt may migrate into the groundwater. For block pavers such as "grasscrete©," plowing may be challenging because the edge of the snow plow blade can catch the edge of the blocks, damaging the surface. This is not to say that it is impossible to use porous pavement in cold climates. Porous pavement has been used successfully in Norway (Stenmark, 1995), incorporating design features to reduce frost heave. Furthermore, some experience suggests that snow melts faster on a porous surface because of rapid drainage below the snow surface (Cahill Associates, 1993). Another concern in cold climates is that infiltrating runoff below pavement may cause frost heave, although design modifications can reduce this risk.

Ultra Urban Areas

Ultra urban areas are densely developed urban areas in which little pervious surface exists. Porous pavement is a good option for these areas because they consume no land area. They are not ideal for high traffic areas, however, because of the potential for failure due to clogging (Galli, 1992).

Stormwater Hotspots

Stormwater hotspots are areas where land use or activities generate highly contaminated runoff, with concentrations of pollutants in excess of those typically found in stormwater. These areas include: commercial nurseries, auto recycle facilities, commercial parking lots, fueling stations, feet storage areas, industrial rooftops, marinas, outdoor container storage of liquids, outdoor loading/unloading facilities, public works storage areas, hazardous materials generators (if containers are exposed to rainfall), vehicle service and maintenance areas, and vehicle and equipment washing/steam cleaning facilities. Since porous pavement is an infiltration practice, it should not be applied on stormwater hotspots due to the potential for groundwater contamination.

Stormwater Retrofit

A stormwater retrofit is a stormwater management practice installed after development has occurred, to improve water quality, protect downstream channels, reduce flooding, or meet other watershed restoration objectives. Since porous pavement can only be applied to relatively small sites, use porous pavement as a primary or widespread method for watershed retrofitting would be expensive. The best application of porous pavement for retrofits is on individual sites where a parking lot is being resurfaced.

Cold Water (Trout) Streams

Porous pavement can help to reduce the increased temperature commonly associated with increased impervious cover. Stormwater runoff ponds on the surface of conventional pavement, and is subsequently heated by the sun and hot pavement surface. By rapidly infiltrating rainfall, porous pavement can reduce the time that stormwater is exposed to the sun and heat.

Siting and Design Considerations

Siting Considerations
Porous pavement has site constraints as other infiltration practices (see Infiltration Trench Fact Sheet). A potential porous pavement site needs to meet the following criteria:

- Soils need to have a permeability between 0.5 and 3.0 inches per hour.
- The bottom of the stone reservoir should be completely flat so that infiltrated runoff will be able to infiltrate through the entire surface.
- Porous pavement should be located at least 2 to 5 feet above the seasonally high groundwater table, and at least 100 feet away from drinking water wells.
- Porous pavement should be located only on low traffic or overflow parking areas, which are expected to be not sanded during wintertime conditions.

Design Considerations

Five basic features should be incorporated into all porous pavement practices: *pretreatment, treatment*, *conveyance*, *maintenance reduction*, and *landscaping* (for more information see the Manual Builder Category).

Pretreatment

In most porous pavement designs, the pavement itself acts as pretreatment to the stone reservoir below. Because the surface serves this purpose, frequent maintenance of the pavement surface is critical to prevent clogging. Another pretreatment element is a fine gravel layer above the coarse gravel treatment reservoir. The effectiveness of both of these pretreatment measures are marginal, which is one reason frequent vacuum sweeping is needed to keep the surface clean.

One design option incorporates an "overflow edge," which is a trench surrounding the edge of the pavement. The trench connects to the stone reservoir below the surface of the pavement. Although this feature does not in itself reduce maintenance requirements, it acts as a backup in case the surface clogs. If the surface clogs, stormwater will flow over the surface and into the trench, where some infiltration and treatment will occur.

Treatment

The stone reservoir below the pavement surface should be composed of layers of small stone directly below the pavement surface, and the stone bed below the permeable surface should be sized to attenuate storm flows for the storm event to be treated. Typically, porous pavement is sized to treat a small event, such as the *water quality storm* (i.e., the storm that will be treated for pollutant removal) which can range from 0.5" to 1.5". Like *infiltration trenches*, water can only be stored in the void spaces of the stone reservoir.

Conveyance

Water is conveyed to the stone reservoir through the surface of the pavement, and infiltrates into the ground through the bottom of this stone reservoir. A geosynthetic liner and sand layer should be placed below the stone reservoir to prevent preferential flow paths and to maintain a flat bottom. Designs also need some method to convey larger storms to the storm drain system. One option is to set storm drain inlets slightly above the surface elevation of the pavement. This allows for temporary ponding above the surface if the surface clogs, but bypasses larger flows that are too large to be treated by the system.

Maintenance Reduction

One non-structural component that can help ensure proper maintenance of porous pavement is the use of a carefully worded maintenance agreement that provides specific guidance to the parking lot, including how to conduct routine maintenance, and how the surface should be repaved. Ideally, signs should be posted on the site identifying porous pavement areas.

Landscaping

The most important landscaping objective for porous pavements is to ensure that its drainage area is fully stabilized, thereby preventing sediment loads from clogging the pavement.

Design Variations

Treat Other Sources

In one design variation, the stone reservoir below the filter can also treat runoff from other sources such as rooftop runoff. In this design, pipes are connected to the stone reservoir to direct flow throughout the bottom of the storage reservoir (Cahill Associates, 1993; Schueler, 1987). If used to treat off-site runoff, porous pavement should incorporate pretreatment, as with all structural management practices.

Regional Adaptations
In cold climates, the base of the stone reservoir should extend below the frost line to reduce the risk of frost heave.

Limitations

In addition to the relatively strict site constraints for porous pavement, a major limitation to the practice is the poor failure rate it has experienced in the field. Several studies indicate that, with proper maintenance, porous pavement can retain its permeability (e.g., Goforth et al., 1983; Gburek and Urban, 1980; Hossain and Scofield, 1991). When porous pavement has been implemented in communities, however, the failure rate has been as high as 75% over two years (Galli, 1992).

Maintenance

Porous pavement requires extensive maintenance compared with other practices. In addition to owners not being aware of porous pavement on a site, not performing these maintenance activities is the chief reason for failure of this practice. Typical requirements follow below:

Table 1. Typical Maintenance Activities for Porous Pavement (Source: WMI, 1997)

Activity	Schedule
• Avoid sealing or repaving with non-porous materials	N/A
• Ensure that paving area is clean of debris • Ensure that paving dewaters between storms • Ensure that the area is clean of sediments	Monthly
• Mow upland and adjacent areas, and seed bare areas • Vacuum Sweep frequently to keep the surface free of sediment • (Typically three to four times per year)	As needed
• Inspect the surface for deterioration or spalling	Annual

Effectiveness

Porous pavement can be used to provide groundwater recharge and to reduce pollutants in stormwater runoff. Some data suggest that as much as 70% to 80% of annual rainfall will go toward groundwater recharge (Gburek and Urban, 1980). These data will vary depending on design characteristics and underlying soils. They both suggest high pollutant removal, although it is difficult to extract these results to all applications of the practice.

Table 2. Pollutant Removal of Porous Pavement (%) Winer (2000)

Pollutant	

	Pollutant Removal (%)[1]
TSS	95
TP	65
TN	82
NOx	NA
Metals	98 - 99
Bacteria	NA
1: Data based on fewer than five data points	

Cost Considerations

Porous pavement is significantly more expensive than traditional asphalt. While traditional asphalt is approximately 50¢ to $1.00 per square foot, porous pavement can range from $2 to $3 per square foot, depending on the design (CWP, 1998; Schueler, 1987). Subtracting the cost of traditional pavement, this amounts to approximately $45,000 and $100,000 per impervious acre treated, which would be quite expensive. On the other hand, porous pavement can create savings in terms of storm drain costs and land consumption. In addition, the cost of vacuum sweeping may be substantial if a community does not already perform vacuum sweeping operations.

References

Cahill Associates. 1993. Stormwater Management Systems: Porous Pavement with Underground Recharge Beds. West Chester, PA

Center for Watershed Protection (CWP). 1998. *Better Site Design: A Handbook for Changing Development Rules in Your Community.* Center for Watershed Protection, Ellicott City, MD.

Center for Watershed Protection (CWP). 1997. Stormwater BMP Design Supplement for Cold Climates. Prepared for: US EPA Office of Wetlands, Oceans and Watersheds. Washington, DC.

Galli, .J. 1992. Preliminary Analysis of the Performance and Longevity of Urban BMPs Installed In Prince George's County, Maryland. Prepared for the Department of Natural Resources. Prince George's County, MD.

Gburek, W. and J. Urban, 1980. Storm Water Detention and Groundwater Recharge Using Porous Asphalt - Experimental Site. For: USDA-SEA-AR Northeast Watershed Research Center, University Park, PA. International Symposium on Urban Storm Runoff. University of Kentucky.

Goforth, G., E. Diniz, and J. Rauhut. Stormwater Hydrological Characteristics of Porous and Conventional Paving Systems. Prepared for: US EPA Office of Research and Development. Cincinnati, OH.

Hossain, M. and L. Scofield, 1991. Porous Pavement for Control of Highway Runoff. Arizona Department of Transportation. Phoenix, AZ

Schueler, T. 1987. Controlling Urban Runoff: A Practical manual for Planning and Designing Urban BMPs. Metropolitan Washington Council of Governments. Washington, DC

Stenmark, C. 1995. An Alternative Road Construction for Stormwater Management. Water Science and Technology, 32(1): 79-84.

Watershed Management Institute (WMI). 1997. Operation, Maintenance, and Management of Stormwater Management Systems. Prepared for: US EPA Office of Water. Washington, DC.

Better Site Design Fact Sheet: Alternative Pavers

Description

Alternative pavers are permeable or semi-permeable surfaces that can replace asphalt and concrete and can be used for driveways, parking lots and walkways. From a stormwater perspective, this is important because alternative pavers can replace impervious surfaces, creating less stormwater runoff. The two broad categories of alternative pavers are paving blocks and other surfaces including gravel, cobbles, wood, mulch, brick, and natural stone. While porous pavement is an alternative paver, as an engineered stormwater management practice, it is discussed in detail in the Porous Pavement Fact Sheet.

Paving blocks

Paving blocks are cement or plastic grids with gaps between them. Paving blocks make the surface more rigid and gravel or grass planted inside the holes allows for infiltration. Depending on the use and soil types, a gravel layer can be added underneath to prevent settling and allow further infiltration.

Other alternative surfaces

Gravel, cobbles, wood, and mulch also allow varying degrees of infiltration. Brick and natural stone arranged in a loose configuration allow for some infiltration through the gaps. Gravel and cobbles can be used as driveway material and wood and mulch can be used to provide walking trails.

Applicability

Alternative pavers can replace conventional asphalt or concrete in parking lots, driveways, and walkways. At the same time, traffic volume and type can limit application. For this reason, alternative pavers for parking are recommended only for overflow areas. In residential areas, alternative surfaces can be used for driveways and walkways, but are not ideal for areas that require handicap accessibility.

Siting and Design Criteria

Accessibility, climate, soil type, traffic volume and long term performance should be considered along with costs and stormwater quality controls when choosing paving materials. Use of alternative pavers in cold climates will require special consideration since snow shovels are not practical for many of these surfaces. Sand is particularly troublesome if used with paving blocks since the sand that ends up in between the blocks cannot effectively wash away or be removed. In addition, salt used to deice can also infiltrate directly into the soil and cause potential groundwater pollution.

Soil types will affect the infiltration rates and should also be considered when using alternative pavers. Clayey soils (D soils) will limit the infiltration on a site. If groundwater pollution is a concern, use of alternative pavers with porous soils should be carefully considered.

The durability and maintenance cost of alternative pavers also limits use to low traffic volume areas. At the same time, alternative pavers can abate stormwater management costs. Used in combination with other better site design techniques, the cumulative effect on stormwater can be dramatic.

Benefits

The most obvious benefit of utilizing alternative pavers includes reduction or elimination of other stormwater management techniques. Applied in combination with other techniques like bioretention and green parking, pollutant removal and stormwater management can be further improved. (See Bioretention and Green Parking Fact Sheets for more information.)

Limitations

Alternative pavers are not recommended for high traffic volumes for durability reasons. Access for wheelchairs is limited with alternative pavers. In addition, snow removal is also difficult since plows cannot be used, sand can cause the system to clog, and salt can be a potential pollutant.

Effectiveness

Alternative pavers all provide better water quality effectiveness than conventional asphalt or concrete and the range of effectiveness depend on the type of paver used. Table 1 provides a list of pavers and the range of water quality effectiveness achievable by different types of alternative pavers.

Table 1. Water Quality Effectiveness of Various Pavers (BASMAA, 1998)

Material	Water Quality Effectiveness
Conventional Asphalt/ Concrete	Low
Brick (in a loose configuration)	Medium
Natural Stone	Medium
Gravel	High
Wood Mulch	High
Cobbles	Medium

Costs

The range of installation and maintenance costs of various pavers is provided in Table 2. Depending on the material used, installation costs can be higher or lower for alternative pavers than conventional asphalt or concrete, but maintenance costs are almost always higher.

Table 2. Installation and Maintenance Costs for Various Pavers (BASMAA, 1997)

Material	Installation Cost	Maintenance Cost
Conventional Asphalt/ Concrete	Medium	Low
Brick (in a loose configuration)	High	Medium
Natural Stone	High	Medium
Gravel	Low	Medium
Wood Mulch	Low	Medium
Cobbles	Low	Medium

References

Bay Area Stormwater Management Agencies Association (BASMAA). *Start at the Source: Residential Site Planning and Design Guidance Manual for Stormwater Quality Protection*. BASMAA, San Francisco, CA. January 1997.

Center for Watershed Protection. *Better Site Design: A Handbook for Changing Development Rules in Your Community.* Center for Watershed Protection, Inc., Ellicott City, MD. 1998.

Schueler, Thomas R. *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs.* Metropolitan Washington Council of Governments, Washington, DC. 1987.

Schueler, Thomas R. *Urban Runoff in the Washington Metropolitan Area.* Metropolitan Washington Council of Governments, Washington, DC. 1983.

Smith, David R. *Life Cycle and Energy Comparison of Grass Pavement and Asphalt Based on Data and Experience from the Green Parking Lot.* The Heritage Conservation and Recreation Service, Order No. A-4331-4. 1981.

Smith, David R. and Sholtis, David A. *An Experimental Installation of Grass Pavement.* The Heritage Conservation and Recreation Service, Order No. A-4331-4. 1981.

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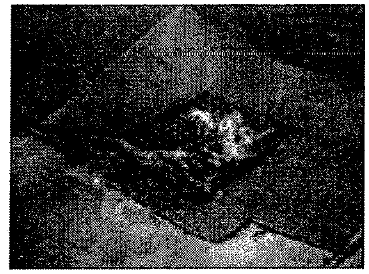
Watershed Benefits of Permeable Pavers

Typical scenario...

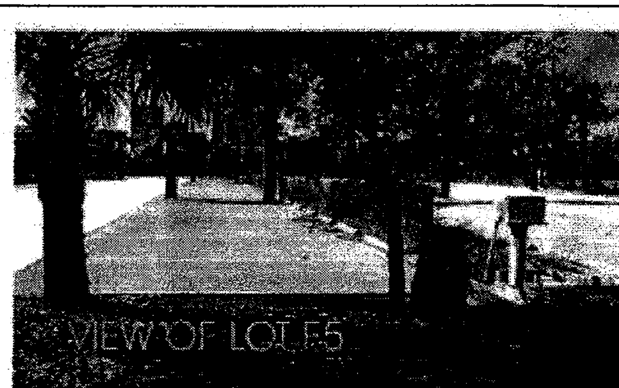


Most of the 'paving over' in developed areas is due to common roads and parking lots, which play a major role in transporting increased stormwater runoff and contaminant loads to receiving waters. Alternative paving materials can be used to locally infiltrate rainwater and reduce the runoff leaving a site. This can help to decrease downstream flooding, the frequency of combined sewer overflow (CSO) events, and the thermal pollution of sensitive waters. Use of these materials can also eliminate problems with standing water, provide for groundwater recharge, control erosion of streambeds and riverbanks, facilitate pollutant removal, and provide for a more aesthetically pleasing site. The effective imperviousness of any given project is reduced while land use is maximized. Alternative pavers can even eliminate the requirement for underground sewer pipes and conventional stormwater retention / detention systems. The drainage of paved areas and traffic surfaces by means of permeable systems is an important building block within an overall Low Impact Development scheme that seeks to achieve a stormwater management system close to natural conditions.

...with permeable pavers*

Water Quality

Some current studies on the effectiveness of permeable pavers for reducing Total Suspended Solid (TSS), nutrient, metal and thermal loadings are being conducted in Florida, Toronto, and Washington State.



The parking lot of the Florida Aquarium in Tampa, which serves 700,000 visitors annually, has been innovatively designed as a research and demonstration project for the use of permeable pavers as part of a treatment train approach, comparing three paving surfaces in conjunction with swales.[1] First-year results found that load removal efficiencies for metals (copper, iron, lead, manganese and zinc) ranged from 23 to 59% for asphalt pavement with a swale; 62 to 84% for cement pavement with a swale; and 75 to 92% for porous concrete with a swale. In general, metals were measured at much higher concentrations in the basins paved with asphalt than those paved with cement products. The porous system with a swale also achieved 91% removal efficiency for total suspended solids, higher than the other two paving systems.

Studies at the University of Guelph in Canada have also observed greater pollutant loads from asphalt surfaces than from concrete or permeable pavers. There, a research team led by Professor William James has been performing field and laboratory tests since 1993 on the influence of permeable pavers on runoff pollutant levels and thermal characteristics. They have found that a permeable paver made up of interlocking concrete blocks can significantly reduce the surface runoff loads of such contaminants as nitrite, nitrate, phosphate, phosphorus, metals, BOD, and ammonium.[2] In addition, during a lab simulation, the permeable pavers were found to reduce surface runoff temperatures by 2 to 4 degrees Celsius compared to the runoff from asphalt paving. Since the permeable pavers also increase infiltration, the total heat content of runoff leaving a site is reduced substantially.[3]

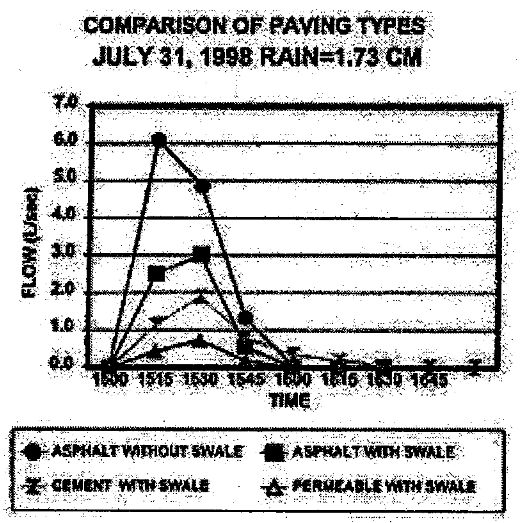
Finally, surface and subsurface runoff samples are being collected by the Center for Urban Water Resources Management in Washington State from a test parking area, which contains five different surface materials.[4] Constructed in 1996, the King County employee parking lot contains nine stalls, of which one is traditional asphalt, and the others are four pairs of alternative permeable pavement surfaces: gravel-filled interlocking concrete blocks, soil and grass-filled interlocking concrete blocks, gravel-filled plastic cell networks, and soil and grass-filled plastic cell networks.

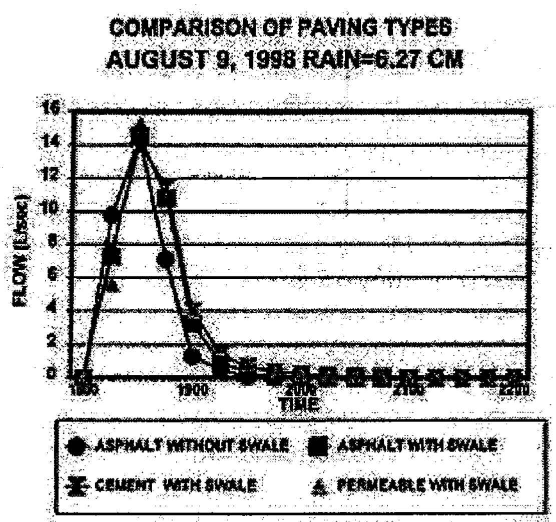
The project's primary goal is to determine the long-term water quality benefits of these systems under real world usage. A system of pipes, gutters and gauges collect and enable the measurement of the volume and chemistry of both the surface runoff and the subsurface infiltrate. A comprehensive water quality analysis is being conducted over the winter of 2001/2002. Preliminary results indicate that the subsurface runoff is consistently cleaner than the surface runoff; statistical analyses and reports will be produced in future months (*Derek Booth, Feb. 2002, personal communication*).

For more specialized users, continuing research at Coventry University in England has been looking at applying nutrients to permeable pavers in order to support a microbial population that can serve as an *in-situ* bioreactor for oil degradation in highway and parking lot runoff.[5] Studies have demonstrated the potential to maintain microbial activity for over 12 months from one application of a slow-release fertilizer, with warnings given about ensuring the effective use of the nutrients so that high effluent levels will not cause eutrophication in receiving waters.

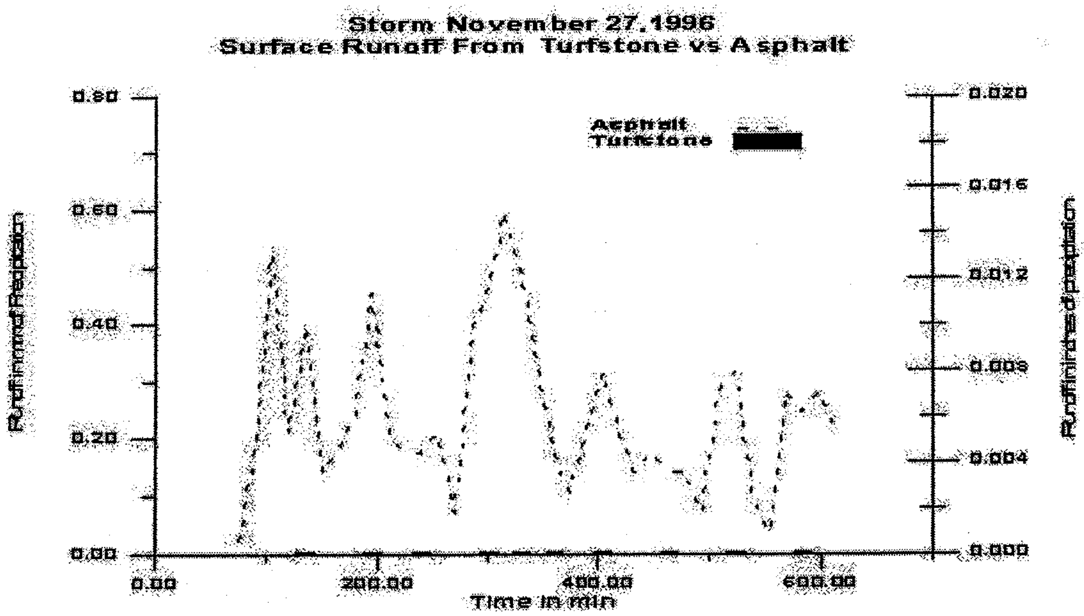
Water Quantity

Most of the above studies have also examined the influence of permeable pavers on runoff volume, tending to show a marked reduction in the surface runoff that leaves a permeable paver site due to increased infiltration. In the University of Guelph experiments, field sites with permeable interlocking concrete pavers demonstrated a 90% reduction in runoff volume.[3] The treatment train studies at the Florida Aquarium showed that, in general, the use of swales reduced runoff volume but that paving type also played a major role in runoff reduction, with permeable pavers being the most effective. The figure below demonstrates this fact as well as the caveat that the use of swales and permeable pavers has the most influence on runoff during small storms.[6] For high intensity rainfalls or when soil conditions are saturated, runoff is not reduced as substantially. Note the different scales on the two graphs; the first is for a rain event that produced just over 0.5 inch of rain in about 75 minutes, while the second is for an event producing almost 2.5 inches in under 2 hours and occurring less than 24 hours after four preceding days with rain.





The studies by the Center for Urban Water Resources Management in Washington State have looked for similar differences in the hydrologic response of pavers based on storm intensity or if the storm followed a long dry period versus a period of abundant rain. To date, however, results show a general absence of surface runoff from the permeable pavers regardless of conditions: "it all just infiltrates, all the time" (*Derek Booth, personal communication*). The figure below, representing a typical observation during the study's first year, compares surface runoff produced from traditional (asphalt) and permeable (Turfstone) pavements.[7] The Turfstone permeable paver is a 60% impervious surface made up of soil and grass-filled interlocking concrete blocks. The measured surface runoff from the Turfstone is less than 1 percent of the total rainfall and is probably a result of observed leaks in the covering over the collection system. All other permeable pavement systems showed equivalent results. The asphalt paving, however, responds quickly to the rainfall, with most of the rain that hits the surface running off.



It is likely that results are different from those in Florida due to differences in the two regions' rainfall regimes. The Washington rain event had a maximum rainfall intensity that was under 0.2 in/hr; this was typical of the storms recorded. In comparison, the heavier rain event presented in the Florida graph had a maximum rainfall intensity of 1.5 in/hr. Rain events in Washington State are generally of a lower intensity and longer duration than those measured in Florida, where the rainfall, particularly in the summer, is dominated by short and more intense convective events.

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* all six photographs from UNI Eco-Stone® Permeable Concrete Pavers PowerPoint presentations, ©2000 UNI-GROUP U.S.A. www.uni-groupusa.org

[1] Rushton, B.T., 2001: Low-impact parking lot design reduces runoff and pollutant loads. *Journal of Water Resources Planning and Management*, (May/June), 172-179.

[2] James, W., ed., 1997: *Advances in Modeling the Management of Stormwater Impacts Volume 5*. Proceedings of the Stormwater and Water Quality Management Modeling Conference, Toronto, Ontario, February 22-23, 1996, 520 pp.

[3] James, W., 2002: Green roads: Research into Permeable Pavers. *Stormwater*, (March/April), 48-50.

[4] Booth, D.B., J. Leavitt and K. Peterson, 1996: *The University of Washington Permeable Pavement Demonstration Project*. Background and First-Year Results, available online at http://dept.washington.edu/cuwrm/ under Research.

[5] Pratt, C.J., A.P. Newman and P.C. Bond, 1999: Mineral oil bio-degradation within a permeable pavement: long term observations. *Wat. Sci. Tech.*, 39 (2), 103-109.

[6] Southwest Florida Water Management District, 2001: *Florida Aquarium Parking Lot - A Treatment Train Approach to Stormwater Management*. Final Report for FDEP Contract No. WM 662, Brooksville, Florida, 220 pp.

[7] Booth, D.B. and J. Leavitt, 1999: Field evaluation of permeable paver systems for improved stormwater management. *Journal of the American Planning Association*, 65(3), 314-325.

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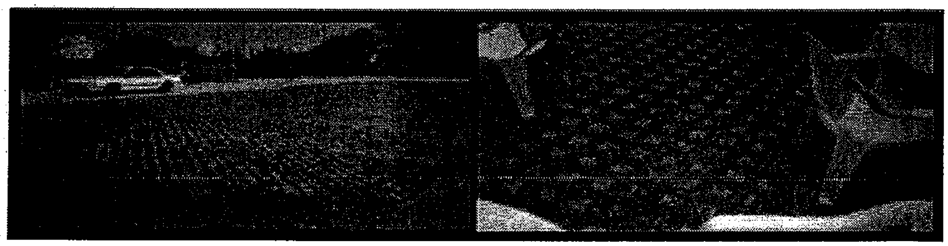
Low Impact Development Center, Inc.

Commercial / Industrial / Institutional Permeable Pavers (Ultra-Urban Retrofits)



DISCLAIMER

BUILD IT!

AUTOCAD
JPEG
SPECIFICATIONS

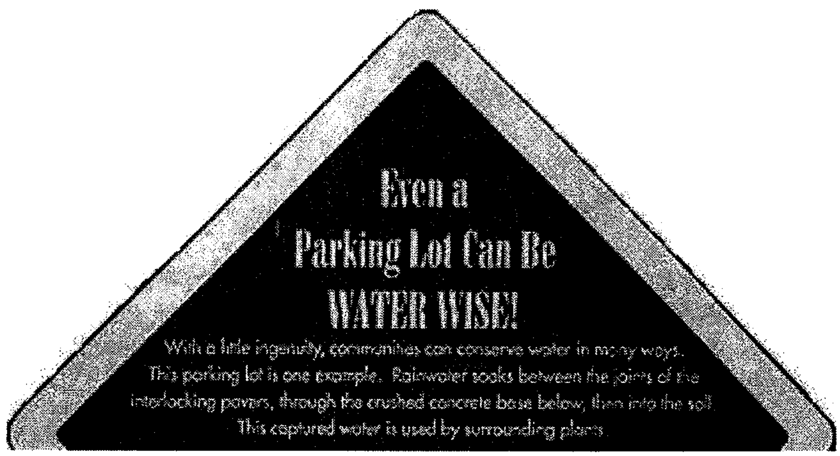
RELATED INFO

SCHEDULE
COSTS
MAINTENANCE

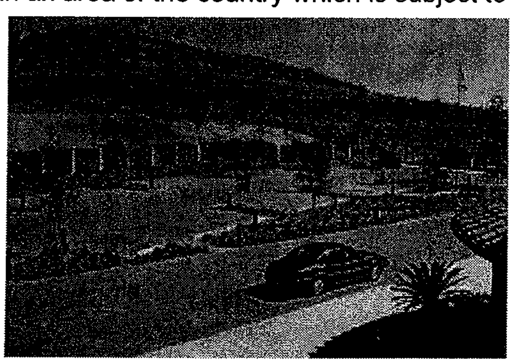
WHY?

BENEFITS

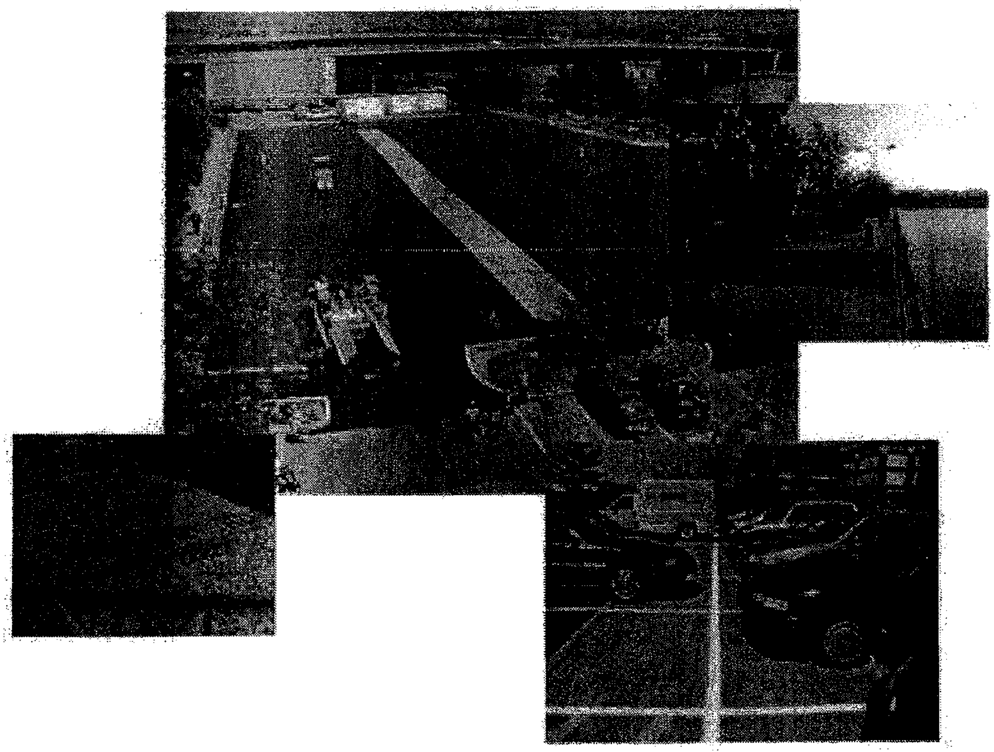
Permeable pavers are well suited for use in commercial and industrial areas, such as parking lots, storage yards, and loading dock areas. They are also very effective for paved surfaces that serve primarily pedestrian traffic - for example, building entryways, plazas and patios. The photographs above demonstrate some examples in North Carolina - a Department of Motor Vehicle lot in Bogue Banks and an outdoor patio in Wrightsville Beach. [1]



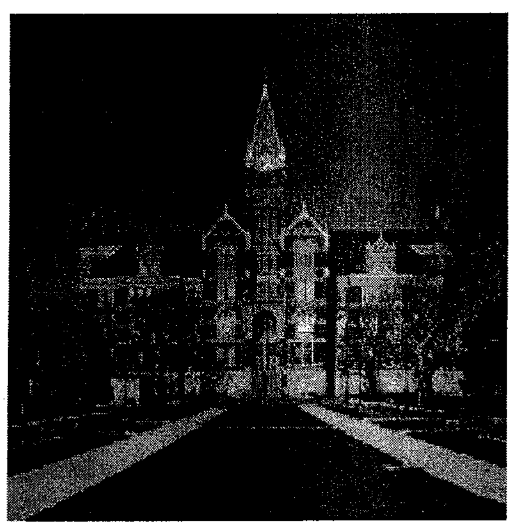
The environmental benefits of these permeable pavers include increased water conservation and improved water quality. For example, in the mid-1990s, as part of their commitment to conservation in an area of the country which is subject to droughts, the **Castaic Lake Water Agency** of southern California used permeable interlocking concrete pavers when building the light-duty parking areas of their new water treatment plant. [2] Existing concrete from the site was crushed and recycled to create the parking lot's base, and the permeable paver system was designed to allow infiltration into the existing soils and drainage towards landscaped islands. In this way, the parking lot also functioned as an effective component of a drought-tolerant landscape.



With an emphasis on water quality, the **Naval District Washington** innovatively applied permeable interlocking concrete paving blocks during its retrofit of an existing parking lot.[3] As part of an overall initiative to help maintain and restore the water quality of the Chesapeake Bay and the Anacostia and Potomac Rivers, permeable pavers were installed between the central rows of the parking lot. This permeable paver strip, shown in the photograph below, required minimal disturbance and maintained parking spaces at existing numbers. It was designed to intercept preferential stormwater pathways and to treat, at a minimum, the first one-half inch of rain from the surrounding impervious parking surfaces. Pollutants are filtered and runoff volume and timing are controlled before discharge of the water to the Anacostia River occurs through the existing storm sewers. LID retrofits such as this are crucial in impervious areas that abut directly to the waterways. The close-up photograph on the right emphasizes the proximity of the parking lot to the river, where untreated runoff has caused severe water pollution problems.



Similar stormwater rehabilitation projects to improve water quality have been undertaken by the **Florida Water Management District** in Tampa Bay, Florida's largest open water estuary.[4] A combination roadway and parking area in North Redington Beach was retrofit with over 9,000 square feet of porous concrete and two 150-foot underdrains during the Bath Club Concourse Stormwater Rehabilitation Project. Before the retrofit, stormwater runoff flowed directly into a single storm sewer, carrying its full load of nonpoint source pollutants directly to Boca Ciega Bay. Besides maximizing the infiltration of stormwater runoff, the project also demonstrated an innovative way to improve the quality of stormwater runoff in highly urbanized areas where conventional stormwater treatment practices, such as detention ponds, are often prohibitively expensive due the high cost of land.



In institutional settings, grass and soil-filled permeable pavers can provide an aesthetic and functional alternative to traditional pavement. **Friends University** in Wichita, Kansas, made use of this Low Impact Development practice when, as part of their renovation of a historic building on campus, they removed the large driveway leading up to the building's main entrance.[5] They replaced it with a system of GEOBLOCK® interlocking plastic cells, which are made up of 98% post consumer recycled materials and filled with topsoil and vegetation. The result was a permeable surface with a lawn appearance, yet one that is capable of bearing heavy emergency or maintenance vehicle loads and providing protection against soil compaction and rutting.

In general, parking lots serve as one of the primary examples for the application of permeable pavers. A mall in Connecticut has made use of a four-acre reinforced grass parking lot with a submerged tank to store stormwater and reuse it in turf irrigation.[6] In Savannah, Georgia, numerous parking lot locations - from libraries and doctor's offices to local businesses - have chosen to apply pervious paving.[7] Gravel-filled or soil and grass-filled plastic cells, interlocking concrete paver blocks, and porous concrete are all suitable for parking areas depending on frequency of use and traffic loads. Some creative designs include a combination of gravel-filled cells or interlocking blocks applied to the parking aisles and turf in the parking stalls.

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1 Photographs taken from the North Carolina State University Cooperative Extension Continuing Education Course on Permeable Pavements developed by Bill Hunt in the Department of Biological & Agricultural Engineering. See http://courses.ncsu.edu/classes-a/bae/cont_ed/pavement_course/index.htm for more information.

2 Photographs and project information from the UNI-GROUP U.S.A. Rio Vista Water Treatment Plant Uni Eco-Stone® Case Study. See http://www.uni-groupusa.org for more information.

3 Natural Resources Defense Council, 2001: *Stormwater Strategies: Community Responses to Runoff Pollution.* http://www.nrdc.org/water/pollution/storm/stoinx.asp

4 U.S. Environmental Protection Agency Office of Wetlands, Oceans and Watersheds Assessment and Watershed Protection Division Nonpoint Source Control, 1994: *Section 319 Nonpoint Source Success Stories Vol. I*, No. 841-S-94-004. Accessible at: http://www.epa.gov/owow/nps/Success319/FL.html.

5 Presto Products Company, 1997: Geoblock® Porous Pavement System - Friends University Uses Porous Pavement System for Renovation of Davis Hall. Accessible at http://www.prestogeo.com.

6 White, P., 1996: A whole lot of turf - permeable paving permits mall expansion in Connecticut. *Turf Magazine*, February. Accessible at Invisible Structures, Inc. Grasspave[2] web site http://www.invisiblestructures.com/GP2/whole_lotof_turf.htm.

7 Krueger, G., 2000: Pervious paving offers one solution to city's flooding problem. *Savannah Morning News*, web posted February 12, 2000. Search the News archives for the Local section at http://www.savannahnow.com/.

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General Permeable Paver Specifications

Click here for Paving Types and Basic Design Considerations

Permeable paver systems typically consist of strong structural materials containing regularly interspersed void areas, which are filled with pervious materials such as gravel or sod. A generalized sketch of a pre-cast castellated concrete paving system is shown. Pre-cast systems can also be made up of lattice grids, or designers can use modular unit pavers, such as interlocking concrete blocks. In addition to these structures, porous concrete is a permeable option that allows for infiltration through the concrete structure itself.

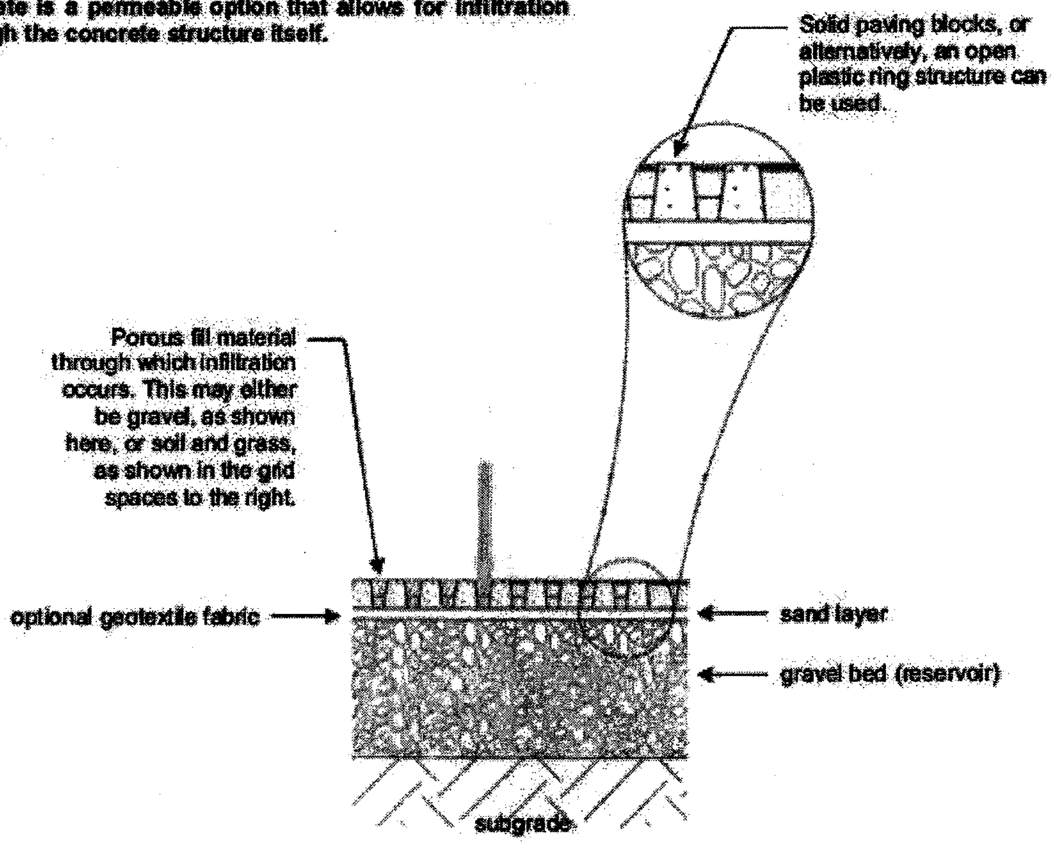

*Image adapted from
SCA Consulting Group, 2000: *Evergreen State College Campus - Toward Zero Impact*
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by SCA Consulting Group, PO BOX 3485, Lacey, WA 98502

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Pavement Types	Basic Design Considerations

Concrete block pavements have been available for many years and have been used primarily as aesthetic treatments to parking areas and low volume roadways. In the last 20 years, high-density plastic grids have also entered the market place. There are many configurations and applications that have been developed for each of these materials. Most of the systems are supported by a stone base that has large pore spaces, such as AASHTO #57 Stone. This base acts both as pavement support and as a reservoir to store water so that it can be infiltrated, if the soil conditions allow, or detained and slowly released to the storm drain system. Supplemental storage facilities, such as underground vaults or drainage blankets, can be used in conjunction with these systems. Each pavement type is generally described below.

- **Porous Concrete:** This pavement has stable air pockets encased within it that allow water to drain uniformly through into the ground below, where it can be naturally filtered. The material becomes stronger and more stable when it gets wet and so does not deteriorate as fast as other paving materials. Its use should be restricted to parking lots and local roads since it supports lighter loads than standard concrete. Since it is cement based, it will not release harmful chemicals into the environment such as with oil-based asphalt. It has been in use throughout Europe for about the last fifty years, and a domestic formula known as the Portland Cement Pervious Pavement has been used successfully since the 1970s in the U.S., particularly in Florida. The pavement is a special blend of Portland cement, sand-free coarse aggregate rock, and water.
- **Grass Pavers:** Plastic rings in a flexible grid system are placed on a base of blended sand, gravel and topsoil, then filled with a topsoil such as sandy loam and planted with vegetation. This pavement gives designers a turfgrass alternative to asphalt or concrete for such low-traffic areas as firelanes, overflow and event parking, golf cart paths, residential driveways, and maintenance and utility access lanes. The support base and the rings' walls prevent soil compaction and reduce rutting and erosion by supporting the weight of traffic and concentrated loads, while the large void spaces in the rings allow a strong root network to develop. The end result is a load-bearing surface covered with natural grass and which is typically around 90% pervious, allowing for stormwater pollution filtration and treatment. Ancillary benefits include

Manufacturers should have detailed design and construction specifications available.

For an excellent web-based course on hydraulic and structural design of permeable pavers, see North Carolina State University Cooperative Extension's Continuing Education Course on Permeable Pavements developed by Bill Hunt in the Department of Biological & Agricultural Engineering.

Site

Permeable pavers have the potential to be used for a wide range of applications including park-and-ride facilities, low volume roads, parking lots, and walkways. The most successful installation of alternative pavements has been stated to be in coastal areas with sandy soils and flatter slopes.[1] In general, the use of permeable pavers requires:

- **low traffic volume**
- **sandy or loamy sand in-situ soil** (Soils that contain significant levels of silt or clay or that are highly compressible, lack cohesion, or expand or contract with moisture may not be feasible for permeable pavers without the use of geotextiles to provide support. A detailed analysis of the soils and feasibility should be conducted when these conditions are encountered.)
- **a seasonally high water table at least 3 to 4 feet from the surface** (Water tables approaching the surface will prevent the water from exfiltrating and can cause structural damage to the system through freeze/frost and floatation processes.)
- **minimal upstream disturbance** (This will prevent clogging of the system, which can significantly shorten the pavers lifetime. Permeable pavers should not be used to treat runoff from large, sparsely vegetated upland areas or areas prone to wind erosion. Sediment control measures should also be carefully followed when upland construction activities take place, and for the longest system lifetime, active street sweeping programs should be employed in the contributing area.)

Load and Gravel Base

When designing the chosen site with permeable pavers, several calculations and considerations must be made. First, the load requirements over the site's expected lifetime must be determined based on the typical vehicle weight, the typical number of vehicle passes per day, and the design life. Most permeable pavement applications will have life spans ranging from 10 to 20 years, with airborne dust capture and reductions in the urban heat island effect. Most manufacturers also produce the paver's rings from post-consumer recycled plastic materials.

- **Gravel Pavers:** This pavement option is intended for high frequency, low speed traffic areas. The same ring structure as with the grass paver is used, but the voids in the rings are filled with gravel in order to provide greater load bearing support for unlimited traffic volumes and/or parking durations. Manufacturers provide specifications on the sieve analysis that should be used to generate the clean gravel fill for the rings, and a geotextile fabric is used to prevent the gravel infill from migrating to the soil subbase. Gravel pavers can be used for automobile and truck storage yards, high-throughput parking lots, service and access areas, loading docks, boat ramps, and outdoor bulk storage areas.
- **Interlocking Concrete Paving Blocks:** The unique shape of these interlocking precast units leaves drainage openings that typically comprise approximately 10% of the paver's surface area. When properly filled with permeable material, the voids allow for drainage of stormwater through the pavement surface into the layers below. The system is a highly durable, yet permeable pavement capable of supporting heavier vehicular loads than grass or gravel pavers and offering the most flexibility in widespread application. Interlocking concrete paving blocks are resistant to heavy loads, easy to repair, require little maintenance, and are of high quality. These systems also have the highest materials and construction costs.

a conservative design life of 10 years recommended as a general rule.[2] The designer must ensure that over this lifetime, the permeable paver system is strong enough to support the applied traffic. Part of this ability will depend on the inherent strength of the actual paver chosen. Generally the design strength of grass and gravel pavers is listed near 5700 psi, interlocking concrete paving blocks are typically designed to meet a minimum of 8000 psi, and porous concrete supports from approximately 1800 to 2400 psi. The other component contributing to system support is the underlying soil strength. Highly permeable soils, such as sands and sandy loams, have the best ability to carry loads. Depending on the paver chosen and the underlying soils, the depth of the system's final gravel base can then be calculated in order to ensure that load requirements are met.

For example, in some locations, a gravel layer may not be needed at all for infrequent car and pick-up truck access, while a layer of approximately 4 to 6 inches depth may be required for infrequent fire truck access. For interlocking concrete paving blocks, certain manufacturers recommend a minimum base of 4 inches for pedestrian applications over well-drained soils and 8 to 10 inches for residential streets. In locations with numerous freeze-thaw cycles, weak soils or an extremely cold climate, a thicker base should be used. The stone and gravel base layer not only provides support but also acts as a storage reservoir to achieve extra detention and serves as a buffer from frost problems.

Infiltration and Water Release

Regional environmental factors, such as the amount and frequency of rainfall and the local soil's permeability, will determine the ability of the paver system to pass stormwater easily through its top layers and then store and release the water in a timely manner into the underlying soil. Whether or not runoff will be generated from the paver for a given storm will depend on the paver's ratio of open to impervious spaces, the storm's precipitation rate, the surface's slope, and the storage capacity in the base layer below. The depth of this storage layer is dictated by the structural considerations discussed above, while the void space in the layer is a function of the stone fill. The system should be designed to infiltrate the design storm and then complete release of the water within at least 48 hours (24 hours is recommended). If the in-situ soil does not allow for release within 48 hours, the site is not suitable for the use of permeable pavers. Possible modifications to the system, however, include the use of an overflow drainage pipe for

	low permeability subgrades and / or for storms exceeding the design storm. Systems can also be designed to drain water away from the pavement to more pervious layers that can accommodate the inflow, to storage areas that allow for slow infiltration, or to a pipe for discharge as filtered stormwater. In situations with a discharge pipe, infiltration does not occur, but the system is used to enhance storage, reduce peak runoff rates and filter pollutants.

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1 EPA, 2000: Low Impact Development (LID) - A Literature Review. EPA-841-B-00-005, Office of Water, Washington, D.C.

2 North Carolina State University Cooperative Extension Continuing Education Course on Permeable Pavements developed by Bill Hunt in the Department of Biological & Agricultural Engineering. See http://courses.ncsu.edu/classes-a/bae/cont_ed/pavement_course/index.htm for more information.

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Strength of Grass Paving Structures

Many designers have questioned the strength of grass paving reinforcement structures to determine suitability for specific traffic and load bearing applications, and to compare products made by different manufacturers.

We at Invisible Structures, Inc. would like to assure you about product strength as a design issue, and clarify all of the data contained in various forms of product information.

All Grass Paving Structures are Strong Enough to Support the Heaviest Vehicles allowed on Highways!

This statement is made after analyzing all of the product specifications in this industry and translating the load bearing test data to a common factor.

We at ISI prefer to use pounds per square inch (psi, or kPa for metric), because it is easy to relate to on a personal level, and it relates directly to tire pressure ratings - the amount of pressure applied to a surface by the tire contact area.

How Much Strength is Needed?
Heavy truck tire pressures for vehicles used on public highways is usually a maximum of 120 psi (827 kPa). These vehicles generally carry loads that average less than 5000 lbs (2268 kg) per tire, which means a contact area usually less than 6.5" x 6.5" (16.5 cm x 16.5 cm). Outriggers, found on fire trucks, are also designed to not exceed this pressure.

ISI's Grasspave^2 product has load bearing strength of 210 psi (1447 kPa) when empty, which provides a safety factor of nearly 2x. Grasspave^2 has the least amount of structural mass to resist loads compared to any other plastic or concrete grass paver, making it the theoretical "weakest". It is the rigid circular "ring" form which maximizes the weight/load bearing ratio of Grasspave^2.

Grass Paver Strength Compared

Product	psi	psf	US Ton/sf	kPa	M Ton/m2
Standard Truck Tire	*120*	*17,280*	*8.64*	*827*	*0.73*
Grasspave2 (filled)	5,720	823,680	411.84	39,411	34.72
Geoblock (heavy)*	420	60,480	30.24	2,894	2.55
Geoblock (light)*	380	54,720	27.36	2,618	2.31
Grassy Paver*	485	69,840	34.92	3,342	2.94
Grassroad Paver8+*	320	46,080	23.04	2,205	1.94
Turfstone (precast)	3,000	432,000	216.00	20,670	18.21

*Note: mfg data not specific-assumed as unfilled.

Add Strength - Fill Paver
It is very rare that a grass paving structure will be used empty or unfilled. Load bearing strength is increased dramatically when the product is filled with sand for part of the root zone medium. As an example, Grasspave^2 strength increased from 210 psi to over 5700 psi (39,273 kPa) when filled with sand and ready for seed (or sand based sod). Thus, the design safety factor goes from 2x to over 47x.

Base Strength is Critical
All grass paving reinforcement structures are designed for two primary functions -

- transfer loads through the walls of the structure to prevent compaction, and
- provide small cellular confinement areas for optimal growth and protection of the grass root zone.

As with other forms of pavement design, grass (porous) paving must be provided with a rigid base below the structure to receive and spread the loads transferred through the structure. Some measurable load spreading capacity exists on the bottom of all grass paving structures, including the flexible grid of Grasspave^2, but we discount this value to simplify calulations and further increase the safety factor.

Calculating the depth and composition of materials for the base course incorporates the same design criteria as for other pavements, such as:

- load bearing capacity of native sub soil,
- plasticity or impact of moisture,
- frost heave potential,
- traffic frequency and/or duration.

Golf carts and pedestrian traffic may require a thin base course (perhaps nothing over sandy gravel soils) which may amount to 2" to 4" (5 - 10 cm) over very weak soils. Buses, trucks and fire trucks can easily require 8" to 12" (20 - 30 cm) or more depth of base course, and frequently the use of a geotextile below the base to prevent integration with sub soils.

Load Factor Equivalents
Assuming a given tire pressure of 120 psi, the following load factors would be equal:

- 17,280 lbs per square foot
- 8.64 tons per square foot
- 20,000 lbs per axle (4 tires)
- 432% of H10 rear axle load
- 216% of H20 rear axle load

Note: an H20 Design Vehicle is theoretical and does not really exist. The axle load would be illegal on most public highways.

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Low Impact Development Center, Inc.

Permeable Paver Costs

Initial expenses for alternative paving materials may be more than if conventional methods are used. However, the use of permeable pavers can often eliminate the requirement for underground storm drain pipes and conventional stormwater systems. Cost savings due to decreased investments in reservoirs, storm sewer extensions, and the repair and maintenance of storm drain systems should be considered. In general, **the multifunctionality of permeable pavers saves money**.

In large jobs, such as shopping parking lots, builders can use permeable pavers as a stormwater management tool, making the job far less expensive than the construction of, for example, a paved surface *and* a stormwater pond. When correctly accounted for, permeable pavers serve both as a necessary structure and part of the stormwater system. If ordinances are written to give builders credit for the stormwater management capabilities of permeable pavers, the job becomes far less expensive than the standard parking lot and retention basin combination.[1] As Bill James, University of Guelph engineering professor states, a water-treatment system can be built right into our roads, providing a way to filter polluted water running off paved surfaces.[2] Land costs are saved, and municipalities gain the added benefits of flood prevention and ground water recharge.[1]

Although the exact amount varies widely, builders can expect an increase in installation costs for permeable pavers relative to asphalt. However, when *all* factors are considered (i.e., decreases in stormwater conveyance and other stormwater management installations), the use of permeable pavers can be cost effective.[3] As a specific example, the use of porous asphalt has been stated to cost about 10 percent more than the use of an equivalent amount of non-porous asphalt. But since the porous asphalt is also part of the drainage system, when the total cost of site development is added up, these permeable systems are said to be able to produce savings of more than 30 percent in favorable sites.[4]

Some on-the-ground success stories include that of Westfarms Mall in Connecticut where a turf parking lot was installed. The mall's general manager reports that she found the cost comparison between grass paving and asphalt to be even at about five years, with a decided turf advantage after that. Most importantly, though, besides reducing stormwater runoff and improving water quality, the four-acre turf parking lot also met the permeable greenspace requirements that were necessary for mall expansion.[5] In addition, the city of Kinston, North Carolina, recently installed over 8,500 square feet of turfstone and grass paver parking. With subgrade materials having similar costs for any type of pavement, the in-place cost for 2" asphalt was estimated at $6,500, while material costs for the permeable pavers came to $6,200 - creating a project comparable or even reduced in costs.[6]

Cost Guides

Data or studies that compare construction, maintenance, and life cycle costs for stormwater management systems are limited. The wide range of site conditions and design requirements also makes it difficult to determine the life cycle cost benefits. It is recommended that each potential application be evaluated on a site-by-site basis. However, a range of cost estimates for the basic installation of permeable paver materials is given in the table below for comparison purposes.[7] The wide range of costs for the paver systems should be noted.

Paver System	Cost Per Square Foot (Installed)
Asphalt	$0.50 to $1.00
Porous Concrete	$2.00 to $6.50
Grass / gravel pavers	$1.50 to $5.75
Interlocking Concrete Paving Blocks	$5.00 to $10.00*

**dependent on depth of base and site accessibility, per conversation with Maryland Unilock® representative (2002)*

Users should also keep in mind that a more accurate price comparison would involve the costs of the full stormwater management paving system. For example, a grass / gravel paver and porous concrete representative stated that when impervious paving costs for drains, reinforced concrete pipes, catch basins, outfalls and stormwater connects are included, an asphalt or conventional concrete stormwater management paving system costs between $9.50 and $11.50 per square foot, compared to a permeable paving stormwater management system at $4.50 to $6.50 a square foot. The savings are considered to be even greater when pervious paving systems are calculated for their stormwater storage; if designed properly, they can eliminate retention pond requirements.[8]

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[1] Krueger, G., 2000: Pervious paving offers one solution to city's flooding problem. *Savannah Morning News*, web posted February 12, 2000. Search the News archives for the Local section at http://www.savannahnow.com/.

[2] Canadian Water and Wastewater Association, 2001: Porous pavement cleans up water run-off: 'Green' roads would improve the environment. *Bulletin*, 15 (5) June. Accessible at http://www.cwwa.ca/bul-old.htm.

[3] North Carolina State University Cooperative Extension Continuing Education Course on Permeable Pavements developed by Bill Hunt in the Department of Biological & Agricultural Engineering. See http://courses.ncsu.edu/classes-a/bae/cont_ed/pavement_course/index.htm for more information.

[4] Ferguson, B.K., 1996: Preventing the problems of urban runoff. *Washington Water RESOURCE, the quarterly report of the Center for Urban Water Resources Management*, 7(4) Fall. Accessible at http://depts.washington.edu/cuwrm/ under Subscriptions.

[5] White, P., 1996: A whole lot of turf - permeable paving permits mall expansion in Connecticut. *Turf Magazine*, February. Accessible at Invisible Structures, Inc. Grasspave[2] web site http://www.invisiblestructures.com/GP2/whole_lotof_turf.htm.

[6] For more information on the project contact Scott Stevens, P.E., Kinston City Engineer at scott.stevens@ci.kinston.nc.us.

[7] Numbers compiled from:

Peterson, C., 2001: Pervious Paving Alternatives. http://www.petrusutr.com/paving_paper.htm.

EPA, 2000: Low Impact Development (LID) - A Literature Review. EPA-841-B-00-005, Office of Water, Washington, D.C.

Booth, D.B., J. Leavitt and K. Peterson, 1997: The University of Washington Permeable Pavement Demonstration Project – Background and First-Year Field Results. Accessible at http://depts.washington.edu/cuwrm/ under Research.

[8] Chere Peterson of PETRUS UTR, Inc., 2002, *personal communication*

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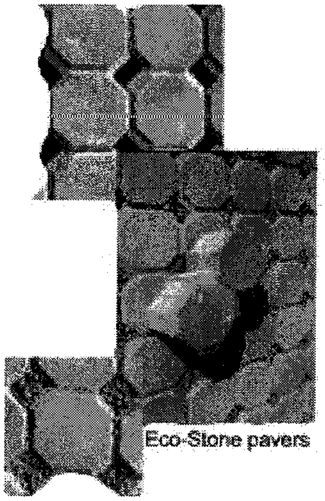
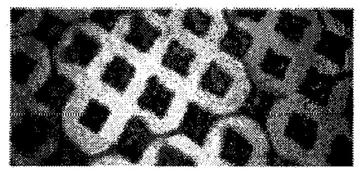
Permeable Pavers Maintenance





After installation of a permeable paver, maintenance is relatively minimal but absolutely necessary to ensure the long lifetime of the system. Grass pavers will require the normal watering and mowing maintenance of any turf system. Porous concrete and interlocking concrete paving blocks require that the surface be kept clean of organic materials (leaves, for example), and periodic vacuuming and low-pressure washing should be used to clear out voids and extend the paver's functional life. Conventional street sweepers should be used with vacuums, brushes and water ideally four (4) times a year, but the actual required frequency will be determined by local conditions. With the interlocking system, additional aggregate fill material may also need to be added after cleaning.

With all of these systems, snow removal operations should be carefully considered, and the use of sand or ash should be avoided as it may cause clogging of the pavement. Plowing requirements for grass or gravel pavers are similar to those of any other unpaved road; in general, the blade must be lifted to clear the grass or gravel surface. A mall in Connecticut with grass paver parking areas custom fit their plows with rollers so that the blade remained about ½ inch off the turf and was able to keep the lot open for winter use.[1] Most manufacturers of permeable paver systems recommend the use of skids on the corners of snowplow blades. Manufacturers of the interlocking pavement blocks, however, state that the structure of the blocks' top edges minimizes chipping and allows for normal plowing procedures. In general, as is always the case, the use of salt can create a potential pollution problem (it is not removed by the permeable paver system), and de-icing products adversely affect all concrete and turf materials.

When installed and maintained properly these systems are durable, although there will be some unavoidable loss in water flow through the system over time. Some settling may also occur in portions of the pavement due to poor compaction or construction control. A high

Example Maintenance Schedule

The primary maintenance requirement for permeable pavers is to clean the surface drainage voids. Fine debris and dirt accumulate in the drainage openings and reduce the pavement's flow capacity. It is natural for clogging to occur over time, but routine maintenance can reduce this problem. A maintenance checklist follows:

- Inspection of the site should occur monthly for the first few months after construction. Then inspections can occur on an annual basis, preferably after rain events when clogging will be obvious.
- Conventional street sweepers equipped with vacuums, water, and brushes can be used to restore permeability. Vacuum sweep ideally four (4) times a year, properly disposing of the removed material. Follow the sweeping with high-pressure hosing of the surface pores. If necessary, add additional aggregate fill material made up of clean gravel.
- Potholes and cracks can be filled with patching mixes, and spot clogging of porous concrete may be fixed by drilling approximately 0.5-inch holes every few feet. Damaged

failure rate for these systems can usually be attributed to poor design, poor construction techniques, subsoils with low permeability, and/or lack of adequate preventative maintenance.[2]

There are plenty of successful installations to turn to as examples, however. In Kinston, North Carolina, a parking lot installed with concrete and grass pavers has been monitored since 1999. Results from this study, along with similar research conducted in other parts of the United States, show that permeable pavement can be very successful at reducing stormwater runoff if proper engineering design, maintenance, and site selection are followed. The Kinston research group recommends that permeable parking lots be maintained at least once per year to ensure the highest level of permeability in the pavement.[3] As a safety measure though, most designs still tend to assume that a reduction in the pavers' infiltration capacity will occur over time due to an accumulation of dirt and debris.

Concerns are often raised with permeable paver systems regarding the potential for groundwater contamination. This is a threat that will depend on the amount of surface contamination, the length of the filtration passage and the purifying effect of the soil.[4] Several studies have shown, however, that most metals are retained on the paver's surface, the geotextile layer or in the upper sediments below the paver system, even after several years of operation, with migration depths varying by constituent.[5,6] The soils beneath the pavers should generally be effective in detaining pollutants from infiltrated water, although for areas of special concern, an impermeable barrier and a collection pipe can be used to transport the filtered water for further treatment or disposal.

interlocking paving blocks can be replaced.
- An active street sweeping program in the site's drainage area will also help to prolong the functional life of the pavement.

Even though some irreplaceable loss in permeability should be expected over the paver's lifetime, you can increase the longevity of the system by following the maintenance schedule for vacuum sweeping and high-pressure washing, restricting the area's use by heavy vehicles, limiting the use of de-icing chemicals and sand, and implementing a stringent sediment control plan.

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[1] White, P., 1996: A whole lot of turf - permeable paving permits mall expansion in Connecticut. *Turf Magazine*, February. Accessible at Invisible Structures, Inc. Grasspave[2] web site http://www.invisiblestructures.com/GP2/whole_lotof_turf.htm.

[2] EPA, 1999: Storm Water Technology Fact Sheet - Porous Pavement. EPA 832-F-99-023, Office of Water, Washington, D.C.

[3] Hunt, B. and Stevens, S., 2001: Permeable pavement use and research at Hannibal Parking Lot in Kinston, N.C. *NWQEP Notes, The NCSU Water Quality Group Newsletter*, (101) May. Accessible at http://www5.bae.ncsu.edu/programs/extension/wqg/issues/Default.htm.

[4] Borgwardt, S., 1999: Survey and expert opinion on the distribution, performance and possible application of porous and permeable paving systems. Report commissioned by MARSHALLS Mono Ltd., West Yorkshire.

[5] Legret, M., V. Colandini and C. Le Marc, 1996: Effects of a porous pavement with reservoir structure on the quality of runoff water and soil. *The Science of the Total Environment*, 189/190, 335-340.

[6] Smith, D.R. and D.A. Sholtis, 1981: Green Parking Lot (Dayton, Ohio) - An Experimental Installation of Grass Pavement. Performance evaluation prepared by the City of Dayton, Ohio. Order No. a-4331-2.

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Permeable Pavers Construction Schedule

The proper installation of permeable paver systems is one of the most crucial steps in ensuring their success. It is recommended that installation of interlocking concrete paving blocks be performed by a contractor experienced with these systems. The interlocking blocks can be installed either manually or mechanically but must be seated and leveled with a vibratory plate compactor. Then the joints and drainage openings are filled with pervious material through a combination of sweeping and vibrating. Grass and gravel pavers, on the other hand, are designed for fast, low-cost installation. They are composed of flexible grids that can be easily installed around obstructions and contours, cut with ordinary hand or power tools, and do not require special fasteners or connection devices, forklifts, cranes or concrete saws.

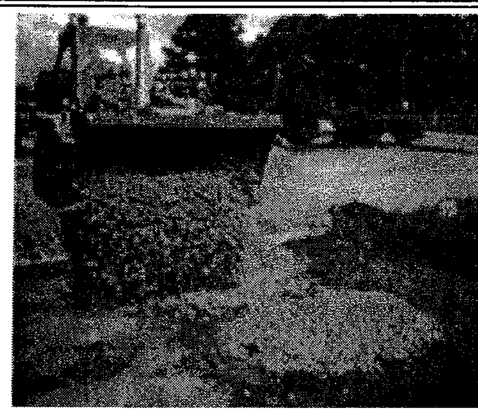
Although porous concrete is not shown in the photographs here, it, in particular, requires high quality control during installation. For example, the amount and timing of the addition of water to the mix is critical, and when improperly done, the mixture is useless as far as permeability. It is absolutely crucial that a project be completed using a certified crew specifically experienced with porous concrete.

Most permeable paver manufacturers include detailed construction specifications from which installation time can be estimated using the project's area and crew size. However, as with all construction activities, total time for installation can be affected by site and weather conditions, timeliness of material shipments, crew productivity, and special installation requirements. While a system based on interlocking concrete paving blocks or gravel pavers is ready for use immediately after installation, grass pavers will typically require several months for proper vegetative growth (sod can be applied for quicker use), and porous concrete requires a covered curing period of about seven days.

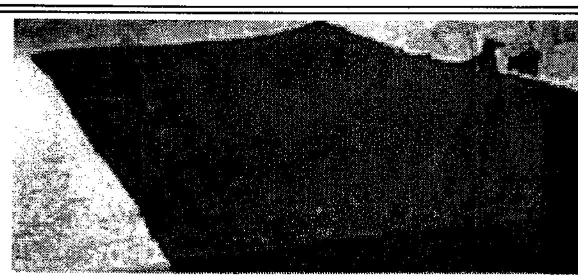
Sequence of Construction*

The first step in construction is excavation. Depths typically range from 8 to 15 inches, with about 12 inches being typical.

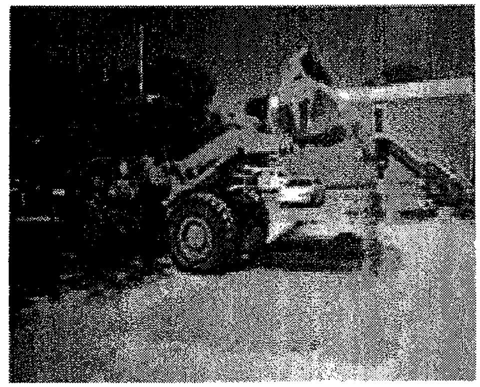
After excavation, the gravel layer is installed, which serves as the strength of the paver system.



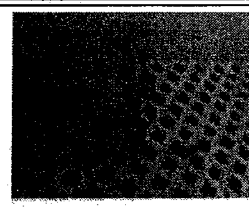
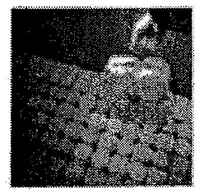
Once the gravel layer is placed, a permeable geotextile fabric can be rolled on top of it.



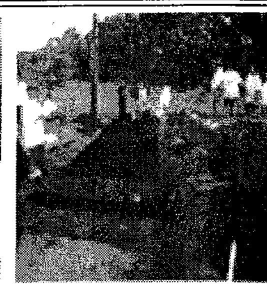
This fabric separates the rock from the overlying sand layer. Wetting of the sand should occur to even out the surface before placement of the pavement grid.



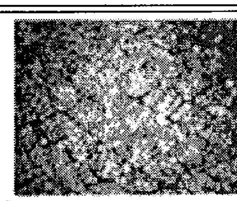
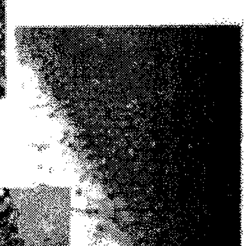
The concrete block or plastic grid layer goes on top of the sand. This layer can be laid by hand...


...or equipment can be used to efficiently lay the interlocking concrete blocks, and certain plastic grid pavers come in spools that are easy to roll.

After the paver grid is placed, the voids are filled with material. Just as with the grid, various fill options are available depending on the system's use and purpose. Pea gravel, larger washed gravel and loamy sand can all be used. For turf pavers, grass root systems tend to flourish once stabilized.

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* Photographs and construction sequence adapted from the North Carolina State University Cooperative Extension Continuing Education Course on Permeable Pavements developed by Bill Hunt in the Department of Biological & Agricultural Engineering. See http://courses.ncsu.edu/classes-a/bae/cont_ed/pavement_course/index.htm for more information. (Additional photos from UNI Eco-Stone® Permeable Concrete Pavers PowerPoint presentations, ©2000 UNI-GROUP U.S.A. www.uni-groupusa.org)

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Geoblock® Porous Pavement System

The **Geoblock® System** is a series of permeable, high-strength, interlocking blocks designed to offer turf protection and load support in traffic areas. The blocks create a flexible structural bridge system within the topsoil layer to support and distribute concentrated loads. Ideal for grass paving and permeable paving in the following applications:

- *Emergency and utility access lanes*
- *Auxiliary parking areas*
- *Trails and trail-hardening systems*
- *Pedestrian walkways and wheelchair access ways*
- *Golf cart path shoulders and aprons*
- *Other High Use Areas where load support and permeability are desired*

Specifications & Features

Your Design and Construction Tools

The following comprehensive design and construction information has been specifically developed and available for your use with the Geoblock® Porous Pavement System. If you would like information mailed to you, please fill out our **literature request form**.

General Brochures/Case Histories

Geoblock® General Overview	An illustrative overview of the Geoblock porous pavement system.
Porous Pavement System Overview	Overview comparing the benefits and applicability of the Geoweb® and Geoblock® systems with a variety of loadings and infill materials.
Case Histories	Project-specific design, construction and performance case histories for the Geoblock system.

Design and Construction Tools

Geoblock® Design and Construction Package	A document tool containing the following design and construction information for the Geoblock system: • *Load Information, Base Recommendations and Design Details* • *Material Specification* • *AutoCAD® Drawings* • *Illustrated Set of Installation Guidelines* • *Time/Cost Worksheet to Calculate Installed Costs* • *Installation Performance Specification*
Geoblock Specification and Features	A web page containing the Geoblock material specifications and product features.
	Build a CSI 3-part format Geoblock specification with ARCAT's SpecWizard™ program. You can view, print and/or download the specification. **ARCAT SpecWizard**
CSI-format Product Specification	A comprehensive product specification in CSI-format based on the Presto Geoblock material specification.
AutoCAD® Drawings	Drawings in DWG format providing all the engineering details needed for plans with the Geoblock system.

For further assistance, contact us by calling 800-548-3424 or 920-738-1336, or by sending us **feedback**.

This site uses Adobe Acrobat documents. If you need Acrobat® Reader, **download** and install the latest version of this free utility from Adobe.

ALCOA

Product or service inquiries
Email **info@prestogeo.com**

Presto Products Company
A Business of Alcoa
670 N Perkins Street, PO Box 2399
Appleton Wisconsin 54912-2399
Ph: 800-548-3424 : 920-738-1336
Fax: 920-738-1222

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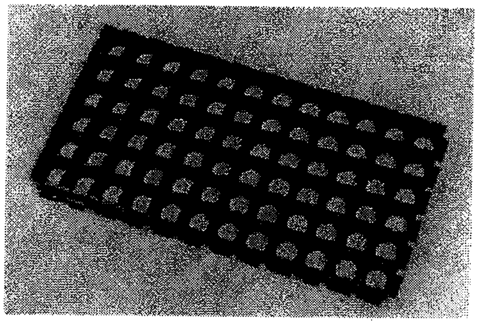
Geoblock® Specifications & Product Features

Geoblock® Product Specifications



- Material Safety Data Sheet

Quality Certification

The Geoblock®5150 product is ISO 9001:2000 certified for the sale, design and manufacture of product from incoming raw materials (resin) to finished product.

ISO 9001:2000 Certified

- **Geoblock Design & Construction**
- **Geoblock CSI-Format Specification**

Specification Development Programs

Two online specification development programs are available for convenience in developing customized specifications.

Presto's SPECMaker® Specification Development Tool

ARCAT's SpecWizard™ Program

Geoblock®5150 Material Specifications

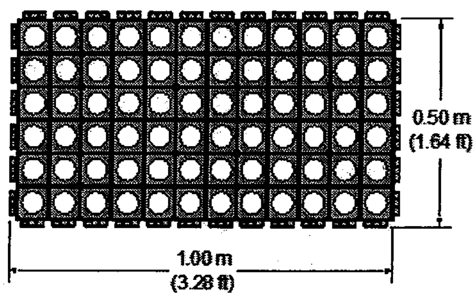
Item	Specifications & Details
Material	Up to 100% Recycled Polyethylene
Color	Ranges from dark shades of gray to black
Chemical Resistance	Superior
Carbon Black for Ultraviolet Light Stabilization	1.5% - 2.0%
Unit Minimum Crush Strength @ 21°C (70°F)	2,900 kPa (420 psi)
Material Flexural Modulus at 23°C (73°F)	240,000 kPa (35,000 psi)
Nominal Dimensions (width x length)	0.50 m x 1.00 m (1.64 ft x 3.28 ft)

Unit Depth	50 mm (1.97 in)
Nominal Coverage Area	0.50 m² (5.38 ft²)
Cells per Unit	72
Cell Size	79 mm x 81 mm (3.1 in x 3.2 in)
Top Open Area per unit	87%
Bottom Open Area per unit	40%
Interlocking offset tabs	1 tab for each peripheral cell
Weight per Unit	4.49 kg (9.9 lb)
Runoff Coefficient @ 63.5 mm/hr (2.5 in) Rainfall	1.5%
Units per Pallet	50
NOTE: Dimensions and weight are subject to manufacturing tolerances and are influenced by recycled component characteristics.	

Geoblock® Product Features / Benefits

The Geoblock® system's unique features perform an important role in two critical aspects of porous pavement systems:

1) Load Support
2) Vegetation Support



Geoblock Unit

1 Load Support

Unit Area

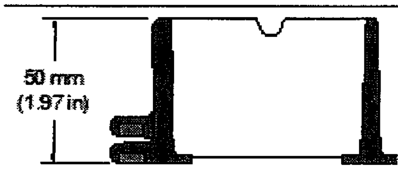
Large surface area per unit .5m x 1.0m (20 x 40 inch nominal) reduces material handling time, increases construction ease and productivity, and decreases installation cost.

Unit Stiffness

Semi-rigid, interconnected cell walls act interdependently to create better distribution of compression, bending and torsional loads.

Tabular Joint

The unique four-sided tabular joint design aids in pattern layout, allowing any side to index together. This construction flexibility increases installation productivity.



Geoblock Cell and Interlocking Offset Tab

The unit's high stiffness and tabular joint system provide unit-to-unit shear transfer of applied load, reducing the pressures on the underlying soil. Greater load transfer results in the need for less

	structural base and less overall installed cost.
	**2 Vegetation Support** **Unit Depth** The 50 mm (2 inch) unit depth creates: 1) a better environment for healthy topsoil, 2) greater protection of the vegetative root zone and 3) protection from soil compaction due to vehicular traffic.

ALCOA

Product or service inquiries

Email **info@prestogeo.com**

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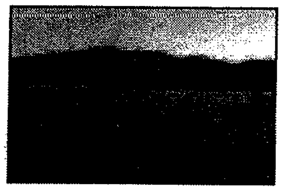
WASHINGTON AGGREGATES & CONCRETE ASSOCIATION

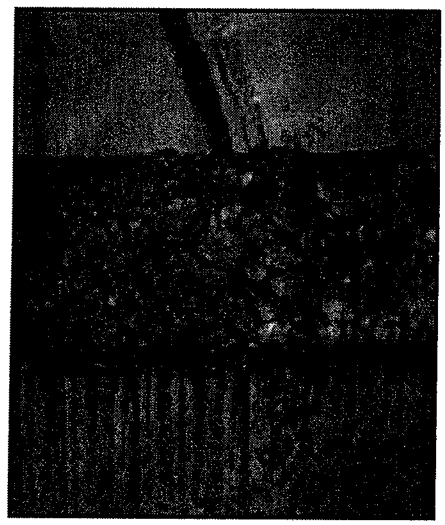
Pervious Pavement



AN ALTERNATIVE STRATEGY ...

FOR CREATING, CAPTURING, TREATING, AND DISCHARGING STORM WATER

Imagine this ...
No Storm Water runoff



Pervious Concrete Pavement allows storm water to pass directly through your concrete pavement. This allows water to infiltrate naturally, recharging local watershed systems, and replenishing ground water supplies while protecting salmon habitat. Pervious Concrete provides an excellent alternative to expensive storm water collection and detention systems with the strength and performance of conventional concrete paving.

PERVIOUS ARTICLE

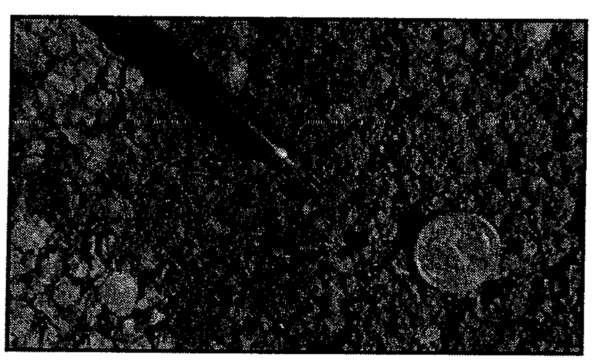
Salmon Listing Requires New Stormwater Management Strat
By BRUCE T. CHAT

Bruce Chattin is the Executive Director of the WACA. He can b reached at (206) 878-1622 or t e-mail.

DOWNLOADS

Pervious Concrete Brochure is available to download as a pdf

What is Pervious Concrete?



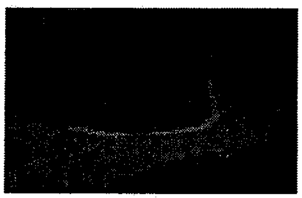
Traditionally reserved for greenhouses and erosion control, Pervious Concrete is a concrete pavement consisting of cement, coarse aggregates, water, and other specialty components to produce sufficient paste and bonding ability to glue coarse aggregates together. This creates an in-place void structure of approximately 14 to 18%. Essentially, Pervious Concrete is a structural concrete pavement that "drinks" water.

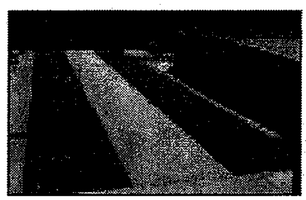
top of page

Why is Pervious Concrete a Sustainable Solution?

- Eliminates untreated storm water and creates zero runoff
- Directly recharges groundwater
- Mitigates first flush pollution
- Protects streams, watersheds, and ecosystems.
- Mimics the drainage and filtration of bioswales and natural soils
- Reduces surface temperatures & heat island effects
- Provides a higher albedo surface reflectivity index (0.35 or higher)
- Eliminates need for expensive collection and detention systems

Designing with Pervious Concrete





Pervious Concrete may be used for: sidewalks, trails, residential driveways, residential streets, gen~~eral park~~ing areas or areas where storm water management is an issue. Generally, Pervious Concrete Pavement depths can range from 4 inches for sidewalks and trails, 5-6 inches for residential driveways and parking lots, and 8-10 inches for heavier truck traffic areas. Depending on the usage, consult: ACI 330 - "Guide for Design & Construction of Concrete Parking Lots".

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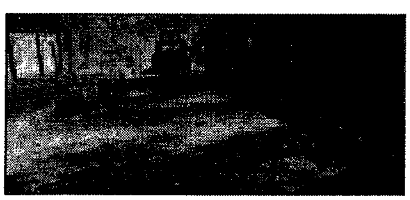
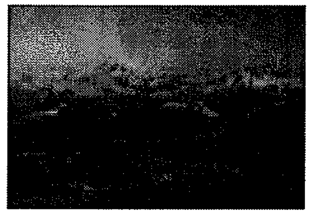
Design of the Retention / Recharge Layer & Subgrade



Pervious Concrete is a 2 part on site storm water management system consisting of the concrete pavement and a coarse gravel retention layer for storm water storage. Design of the retention / recharge area is a site specific task and should take into account, percability and characteristics of native soils, volume of storm water anticipated, rate of flow, and duration. An initial soils site survey, and site specific storm water calculations should be performed by a storm water management engineer.

What About Freeze / Thaw?



Pervious Concrete is not designed nor intended as a storage area. Water passes directly through the pavement and into the retention layer below. Freeze/Thaw is not a concern in western Washington as our temperatures and freeze / thaw conditions are nominal.

top of page

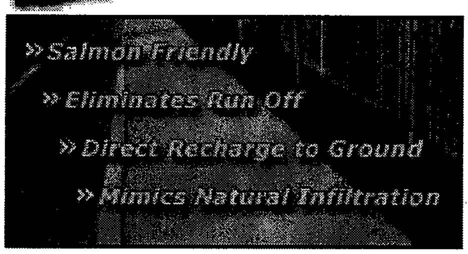
What About Clogging?

Clogging of any pervious surface can be a concern. It is highly unlikely a majority of any pervious surface will become 100% clogged. Water will always seek the next point of infiltration.

What About Maintenance?

Good common sense approaches to prevent placement of landscape materials and cleaning of any pervious surface are recommended practices. For parking areas, your regular parking lot sweeping / vacuuming program should be sufficient.

PERVIOUS CONCRETE WORKS
WITH THE ENVIRONMENT



To learn more about Pervious Concrete Pavement or other concrete and aggregate needs, please contact your local ready mix supplier.

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United States Environmental Protection Agency
Office of Water Washington, D.C.
EPA 832-F-99-023
September 1999

EPA

Storm Water Technology Fact Sheet
Porous Pavement

DESCRIPTION

Porous pavement is a special type of pavement that allows rain and snowmelt to pass through it, thereby reducing the runoff from a site and surrounding areas. In addition, porous pavement filters some pollutants from the runoff if maintained.

There are two types of porous pavement: porous asphalt and pervious concrete. Porous asphalt pavement consists of an open-graded coarse aggregate, bonded together by asphalt cement, with sufficient interconnected voids to make it highly permeable to water. Pervious concrete consists of specially formulated mixtures of Portland cement, uniform, open-graded coarse aggregate, and water. Pervious concrete has enough void space to allow rapid percolation of liquids through the pavement.

The porous pavement surface is typically placed over a highly permeable layer of open-graded gravel and crushed stone. The void spaces in the aggregate layers act as a storage reservoir for runoff. A filter fabric is placed beneath the gravel and stone layers to screen out fine soil particles. Figure 1 illustrates a common porous asphalt pavement installation.

Two common modifications made in designing porous pavement systems are (1) varying the amount of storage in the stone reservoir beneath the pavement and (2) adding perforated pipes near the top of the reservoir to discharge excess storm water after the reservoir has been filled.

Some municipalities have also added storm water reservoirs (in addition to stone reservoirs) beneath the pavement. These reservoirs should be designed to accommodate runoff from a design storm and should provide for infiltration through the underlying subsoil.

APPLICABILITY

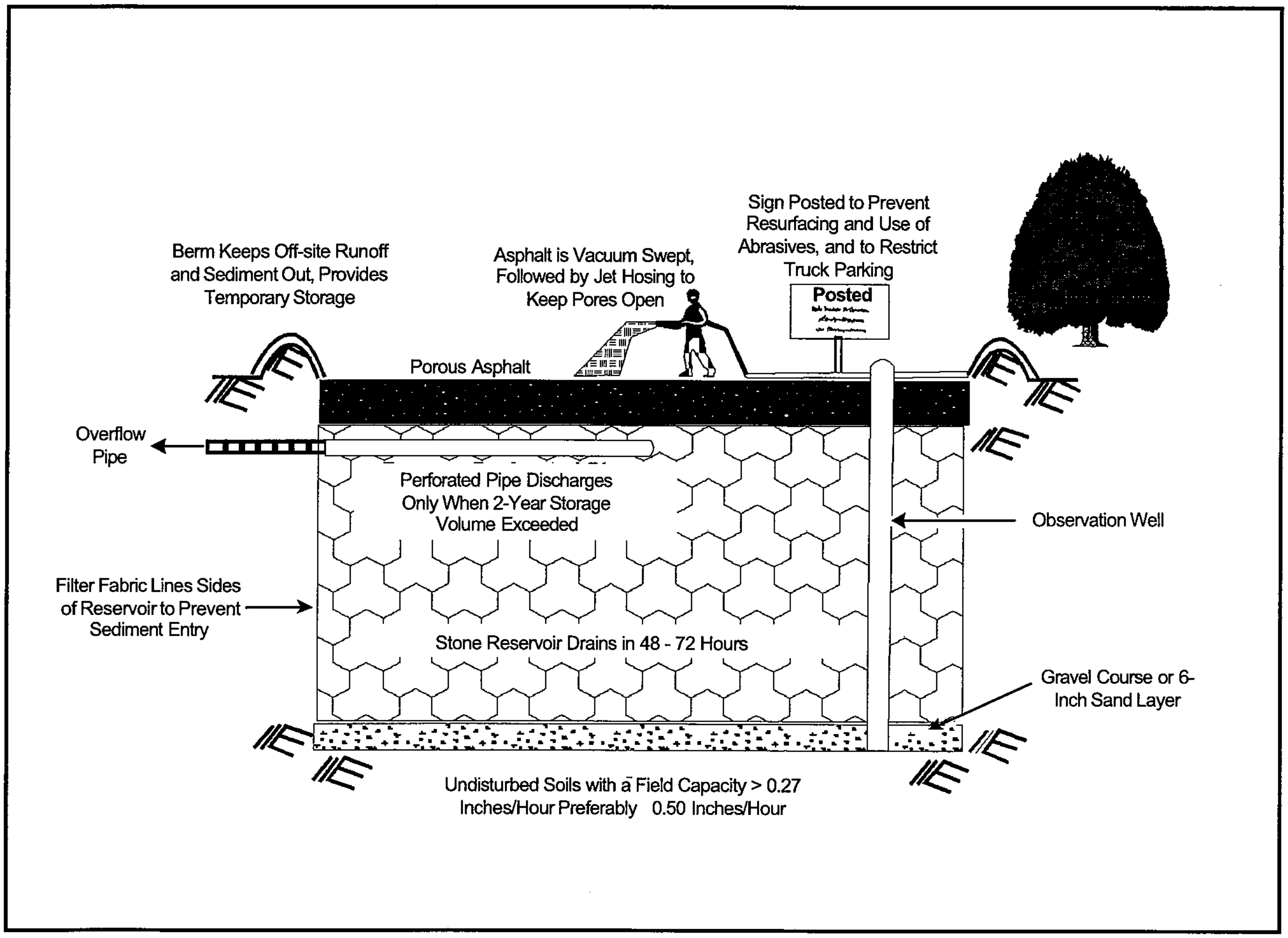
Porous pavement may substitute for conventional pavement on parking areas, areas with light traffic, and the shoulders of airport taxiways a runways, provided that the grades, subsoils, drainage characteristics, and groundwater conditions are suitable. Slopes should be flat or very gentle. Soils should have field-verified permeability rates of greater than 1.3 centimeters (0.5 inches) per hour, and there should be a 1.2 meter (4-foot) minimum clearance from the bottom of the system to bedrock or the water table.

ADVANTAGES AND DISADVANTAGES

The advantages of using porous pavement include:

- Water treatment by pollutant removal.
- Less need for curbing and storm sewers.
- Improved road safety because of better skid resistance.
- Recharge to local aquifers.

The use of porous pavement may be restricted in cold regions, arid regions or regions with high wind erosion rates, and areas of sole-source aquifers. The use of porous pavement is highly constrained, requiring deep permeable soils, restricted traffic, and adjacent land



Source: Modified from MWCOG, 1987.

FIGURE 1 TYPICAL POROUS PAVEMENT INSTALLATION

uses. Some specific disadvantages of porous pavement include the following:

- Many pavement engineers and contractors lack expertise with this technology.
- Porous pavement has a tendency to become clogged if improperly installed or maintained.
- Porous pavement has a high rate of failure.
- There is some risk of contaminating groundwater, depending on soil conditions and aquifer susceptibility.
- Fuel may leak from vehicles and toxic chemicals may leach from asphalt and/or binder surface. Porous pavement systems are not designed to treat these pollutants.
- Some building codes may not allow for its installation.
- Anaerobic conditions may develop in underlying soils if the soils are unable to dry out between storm events. This may impede microbiological decomposition.

As noted above, the use of porous pavement does create risk of groundwater contamination. Pollutants that are not easily trapped, adsorbed, or reduced, such as nitrates and chlorides, may continue to move through the soil profile and into the groundwater, possibly contaminating drinking water supplies. Therefore, until more scientific data is available, it is not advisable to construct porous pavement near groundwater drinking supplies.

In addition to these documented pros and cons of porous pavements, several questions remain regarding their use. These include:

- Whether porous pavement can maintain its porosity over a long period of time, particularly with resurfacing needs and snow removal.
- Whether porous pavement remains capable of removing pollutants after subfreezing weather and snow removal.
- The cost of maintenance and rehabilitation options for restoration of porosity.

DESIGN CRITERIA

Porous pavement - along with other infiltration technologies like infiltration basins and trenches - have demonstrated a short life span. Failures generally have been attributed to poor design, poor construction techniques, subsoils with low permeability, and lack of adequate preventive maintenance. Key design factors that can increase the performance and reduce the risk of failure of porous pavements (and other infiltration technologies) include:

- Site conditions;
- Construction materials; and
- Installation methods.

These factors are discussed further in Table 1.

PERFORMANCE

Porous pavement pollutant removal mechanisms include absorption, straining, and microbiological decomposition in the soil. An estimate of porous pavement pollutant removal efficiency is provided by two long-term monitoring studies conducted in Rockville, MD, and Prince William, VA. These studies indicate removal efficiencies of between 82 and 95 percent for sediment, 65 percent for total phosphorus, and between 80 and 85 percent of total nitrogen. The Rockville, MD, site also indicated high removal rates for zinc, lead, and chemical oxygen demand. Some key factors to increase pollutant removal include:

- Routine vacuum sweeping and high pressure washing (with proper disposal of removed material).
- Drainage time of at least 24 hours.
- Highly permeable soils.
- Pretreatment of runoff from site.
- Organic matter in subsoils.
- Clean-washed aggregate.

Traditionally, porous pavement sites have had a high failure rate - approximately 75 percent. Failure has been attributed to poor design, inadequate construction techniques, soils with low permeability, heavy vehicular traffic, and resurfacing with nonporous pavement materials. Factors enhancing longevity include:

- Vacuum sweeping and high-pressure washing.
- Use in low-intensity parking areas.
- Restrictions on use by heavy vehicles.
- Limited use of de-icing chemicals and sand.
- Resurfacing.
- Inspection and enforcement of specifications during construction.
- Pretreatment of runoff from offsite.
- Implementation of a stringent sediment control plan.

OPERATION AND MAINTENANCE

Porous pavements need to be maintained. Maintenance should include vacuum sweeping at least four times a year (with proper disposal of

TABLE 1 DESIGN CRITERIA FOR POROUS PAVEMENTS

Design Criterion	Guidelines
Site Evaluation	• Take soil boring to a depth of at least 1.2 meters (4 feet) below bottom of stone reservoir to check for soil permeability, porosity, depth of seasonally high water table, and depth to bedrock.
	• Not recommended on slopes greater than 5 percent and best with slopes as flat as possible.
	• Minimum infiltration rate 0.9 meters (3 feet) below bottom of stone reservoir: 1.3 centimeters (0.5 inches) per hour.
	• Minimum depth to bedrock and seasonally high water table: 1.2 meters (4 feet).
	• Minimum setback from water supply wells: 30 meters (100 feet).
	• Minimum setback from building foundations: 3 meters (10 feet) downgradient, 30 meters (100 feet) upgradient.
	• Not recommended in areas where wind erosion supplies significant amounts of windblown sediment.
	• Drainage area should be less than 6.1 hectares (15 acres).
Traffic conditions	• Use for low-volume automobile parking areas and lightly used access roads.
	• Avoid moderate to high traffic areas and significant truck traffic.
	• Avoid snow removal operations; post with signs to restrict the use of sand, salt, and other deicing chemicals typically associated with snow cleaning activities.
Design Storm Storage Volume	• Highly variable; depends upon regulatory requirements. Typically design for storm water runoff volume produced in the tributary watershed by the 6-month, 24-hour duration storm event.
Drainage Time for Design Storm	• Minimum: 12 hours.
	• Maximum: 72 hours.
	• Recommended: 24 hours.
Construction	• Excavate and grade with light equipment with tracks or oversized tires to prevent soil compaction.
	• As needed, divert storm water runoff away from planned pavement area before and during construction.
	• A typical porous pavement cross-section consists of the following layers: 1) porous asphalt course, 5-10 centimeters (2-4 inches) thick; 2) filter aggregate course; 3) reservoir course of 4-8 centimeters (1.5-3-inch) diameter stone; and 4) filter fabric.
Porous Pavement Placement	• Paving temperature: 240° - 260° F.
	• Minimum air temperature: 50° F.
	• Compact with one or two passes of a 10,000-kilogram (10-ton) roller.
	• Prevent any vehicular traffic on pavement for at least two days.
Pretreatment	• Pretreatment recommended to treat runoff from off-site areas. For example, place a 7.6-meter (25-foot) wide vegetative filter strip around the perimeter of the porous pavement where drainage flows onto the pavement surface.

removed material), followed by high-pressure hosing to free pores in the top layer from clogging. Potholes and cracks can be filled with patching mixes unless more than 10 percent of the surface area needs repair. Spot-clogging may be fixed by drilling 1.3 centimeter (half-inch) holes through the porous pavement layer every few feet.

The pavement should be inspected several times during the first few months following installation and annually thereafter. Annual inspections should take place after large storms, when puddles will make any clogging obvious. The condition of adjacent pretreatment devices should also be inspected.

COSTS

The costs associated with developing a porous pavement system are illustrated in Table 2.

Estimated costs for an average annual maintenance program of a porous pavement parking lot are approximately $4,942 per hectare per year ($200 per acre per year). This cost assumes four inspections each year with appropriate jet hosing and vacuum sweeping treatments.

REFERENCES

1. Field, R., et al., 1982. "An Overview of Porous Pavement Research." *Water Resources Bulletin*, Volume 18, No. 2, pp. 265-267.

2. Metropolitan Washington Council of Governments, 1987. *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs.*

3. Metropolitan Washington Council of Governments, 1992. *A Current Assessment of Best Management Practices: Techniques for Reducing Nonpoint Source Pollution in a Coastal Zone.*

4. Southeastern Wisconsin Regional Planning Commission, 1991. *Costs of Urban Nonpoint Source Water Pollution Control Measures*, Technical Report No. 31.

5. U.S. EPA, 1981. *Best Management Practices Implementation Manual.*

TABLE 2 ESTIMATED COSTS FOR A POROUS PAVEMENT SYSTEM

Component	Unit Cost	Total
Excavation Costs	740 cy X $5.00/cy	$3,700
Filter Aggregate/Stone Fill	740 cy X $20.00/cy	$14,800
Filter Fabric	760 sy X $3.00/cy	$2,280
Porous Pavement	556 sy X $13.00/sy	$7,228
Overflow Pipes	200 ft X $12.00/ft	$2,400
Observation Well	1 at $200 each	$200
Grass Buffer	822 sy X $1.50/sy	$1,250
Erosion Control	$1000	$1,000
Subtotal		$32,858
Contingencies (Engineering, Administration, etc.)	25%	$8,215
Total		$41,073

6. U.S. EPA, 1992. *Stormwater Management for Industrial Activities: Developing Pollution Prevention Plans and Best Management Practices*. EPA 833-R-92-006.

7. Washington State Department of Ecology, 1992. *Stormwater Management Manual for the Puget Sound Basin.*

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OWM MTB
MUNICIPAL TECHNOLOGY BRANCH

United States
Environmental Protection Agency

Office of Water (4203)
Washington, DC 20460

EPA-841-B-00-005B
October 2000

Field Evaluation of Permeable Pavements for Stormwater Management

Olympia, Washington

Key Concepts:

- Structural Controls
- Volume Reduction
- Space Savings

LOW-IMPACT DEVELOPMENT CENTER

Introduction

This study demonstrates the potential of permeable pavement systems to restore soil infiltration functions in the urban landscape. It is based on the results of a project that included installing and monitoring several porous pavement systems in a parking area. The project's objectives were to

- Review existing information on permeable pavements
- Construct full-scale test sites
- Evaluate the long-term performance of these systems

The report outlines the difficulties encountered, costs of installing and maintaining the systems, performance based on existing soil systems, special benefits of filling the open cells with grass as opposed to gravel, and other water quality benefits.

Project Area

The demonstration site was in an office parking lot in Olympia, Washington. Two adjacent parking stalls were constructed using four types of permeable pavement systems that consisted of a combination of grass and gravel, as shown in Figure 1. The designs were

1. A flexible system consisting of a plastic network of cells with grass infill and virtually no impervious area coverage.
2. A flexible system consisting of a plastic network of cells similar to design 1 but filled with gravel.

Project Benefits:

- Elimination of Stormwater Ponds
- Demonstration of Water Quality Benefits
- Lower Maintenance

3. A system consisting of impervious blocks with the space between the blocks filled with grass. (Total surface area is 60 percent impervious).
4. A system consisting of impervious blocks with the space between the blocks filled with gravel. (Total surface area is 90 percent impervious).

A control stall was constructed out of traditional asphalt. A system of pipes, gutters, and automatic sampling gauges was installed to collect and measure the quantity and chemistry of surface runoff and subsurface infiltrate. Figure 2 shows a schematic of the test facility.

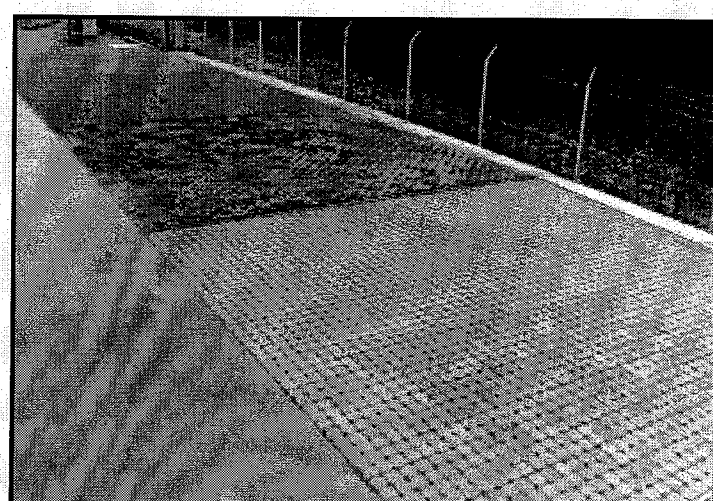

Figure 1. Different types of permeable pavement. From top left: reinforced gravel and grass pavement, reinforced grass pavement, 60% impervious concrete blocks with grass, 90% impervious blocks with gravel.

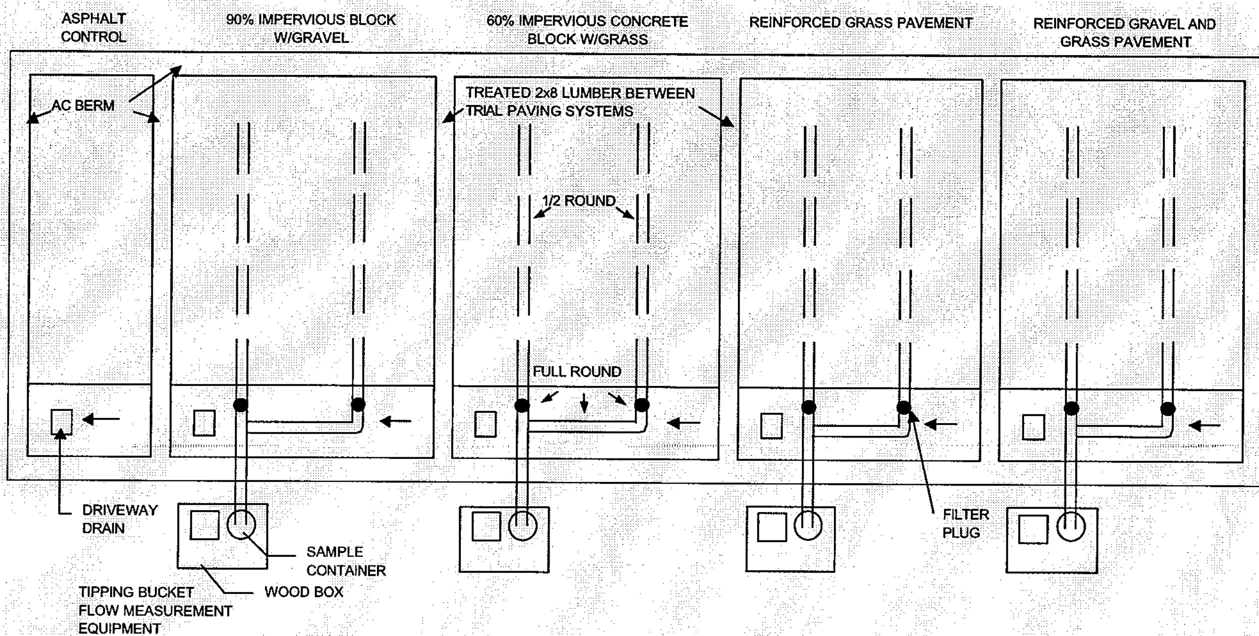

Figure 2. Schematic of the test facility showing treatments and runoff collection devices.

Project Summary and Benefits

The results of this study showed the following relationships:

- The use of permeable pavement systems dramatically reduced surface runoff volume and attenuated the peak discharge, as shown in Figure 3.
- Although there were significant structural differences between the systems, the hydrologic benefits were consistent.
- Storm characteristics and weather conditions influenced the hydrologic responses of the systems.
- Permeable pavement system types vary widely in cost and are more expensive than typical asphalt pavements. Cost comparisons between permeable pavement installations and conventional ponds or underground vaults are limited. However, the elimination of conventional systems and reduced life cycle and maintenance costs can result in significant cost savings over the long term.
- A significant contribution of permeable pavements is the ability to reduce *effective impervious area*, which has a direct connection with downstream drainage systems. This strategy of hydrologic and hydraulic disconnectivity can be used to control runoff timing, reduce runoff volume, and provide water quality benefits.

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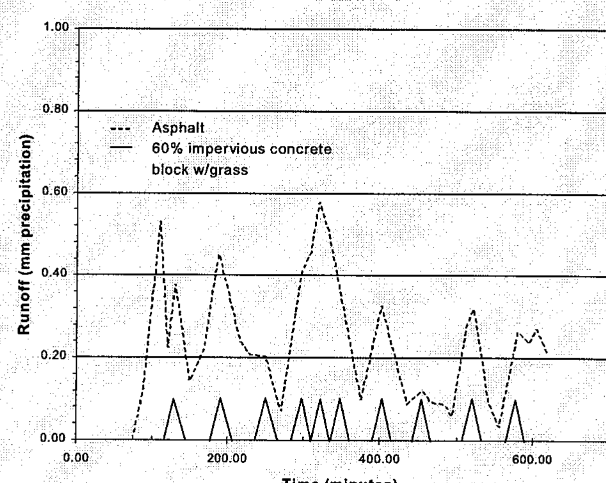

Figure 3. Runoff volumes from asphalt and permeable pavements.

Appendix 8

Permeable Hot-mix Asphalt Sample Specification

Origin: Cahill Associates, Westchester, Pennsylvania (Cahill Associates, Section 02725-General porous paving and groundwater infiltration beds, 2004).

Application: Parking lots with aggregate base for retention storage.

Soil infiltration rate: Required soil infiltration varies depending on contributing area, aggregate base storage and infiltration capacity, and design storm. In general, minimum long-term infiltration rate should be 0.1 inch/hour.

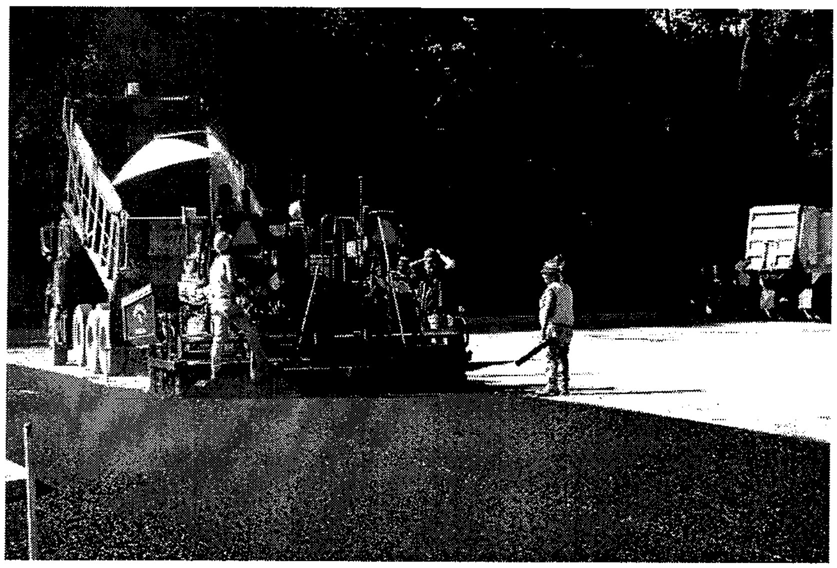

Figure 1 Parking installation, *Courtesy of Cahill Associates*

Top course: 2.5 inches thick

Aggregate grading:	U.S. Standard Sieve	Percent Passing
	1/2	100
	3/8	92-98
	4	32-38
	8	12-18
	16	7-13
	30	0-5
	200	0-3

Bituminous asphalt cement

- 5.75% to 6.00% by weight dry aggregate.
- Drain down of asphalt binder should be no greater than 0.3% in accordance of ASTM D6390.
- Use a neat asphalt binder modified with an elastomeric polymer to produce a binder meeting requirements of performance or PG 76-22 (PG recommendation for mid-Atlantic states).
- Elastomeric polymer is a styrene-butadiene-styrene or equal applied at a rate of 3% by total weight of the binder. Thoroughly blend polymer and binder at asphalt refinery prior to loading and transportation. The polymer modified asphalt binder should be heat and storage stable.
- Hydrated lime is added at a rate of 1.0% by weight of the total dry aggregate to mixes with granite stone to prevent separation of the asphalt from the aggregate and achieve a required tensile strength ratio of at least 80%. Hydrated lime should meet ASTM C 977.
- The asphalt mix should be tested for resistance to stripping by water in accordance with ASTM D 3625. If estimated coating area is not above 95%, anti-stripping agents should be added to the asphalt.

Asphalt installation

- Bituminous surface course mix is laid in one 2.5-inch lift directly over aggregate storage base.
- Laying temperature of the mix should be between 240 and 250 degrees Fahrenheit and ambient temperature should not be below 40 degrees Fahrenheit.
- Compaction of the surface course should occur when the surface is cool enough to resist a 10-ton roller. One or two passes is all that is required for proper compaction and additional rolling can cause a reduction in surface course porosity.

Aggregate base/storage bed material

- Coarse aggregate is 0.5- to 2.5-inch uniformly graded stone with a wash loss of no more than 0.5% (AASHTO size number 3).

  Aggregate grading:

U.S. Standard Sieve	Percent Passing
2 ½"	100
2"	90-100
1 ½"	35-70
1"	0-15
½"	0-5

- Choker base course aggregate should be 3/8- to 3/4-inch uniformly graded stone with a wash loss of no more than 0.5% (AASHTO size number 57).

  Aggregate grading:

U.S. Standard Sieve	Percent Passing
1 ½"	100
1"	95-100
½"	25-60
4	0-10
8	0-5

Aggregate base/storage installation

- Stabilize area and install erosion control to prevent runoff and sediment from entering storage bed.
- Existing subgrade under base should NOT be compacted or subject to excessive construction equipment traffic prior to installation.

- Storage bed should be excavated level to allow even distribution of water and maximize ~~infiltration~~ across parking entire area.
- Immediately before base aggregate and asphalt placement remove any accumulation of fine material from erosion with light equipment and scarify soil to a minimum depth of 6 inches.
- Geotextile fabric is a Mirafi 160N or approved equal. Overlap adjacent strips 16 inches and secure fabric 4 feet outside of storage bed to reduce sediment input to bottom of area.
- Install course (0.5 to 2.5 inch, AASHTO size number 3) aggregate in lifts no greater than 8 inches and lightly compact each lift.
- Install 1-inch choker course (No. 8 to 1.5-inch aggregate, AASHTO size number 57) evenly over surface of course aggregate base.
- Storage and infiltration bed depth will depend on infiltration rates, storage requirement and design storm; however, Cahill Associates often install 18- to 36-inch sections designed for full retention of storm flows.
- All erosion and sediment control should remain in place until area is completely stabilized with soil amendments, landscaping or other approved controls.

Backup systems

- For backup infiltration capacity (in case the asphalt top course becomes clogged) an unpaved stone edge is usually installed that is hydrologically connected to the storage bed (see Figure 2).

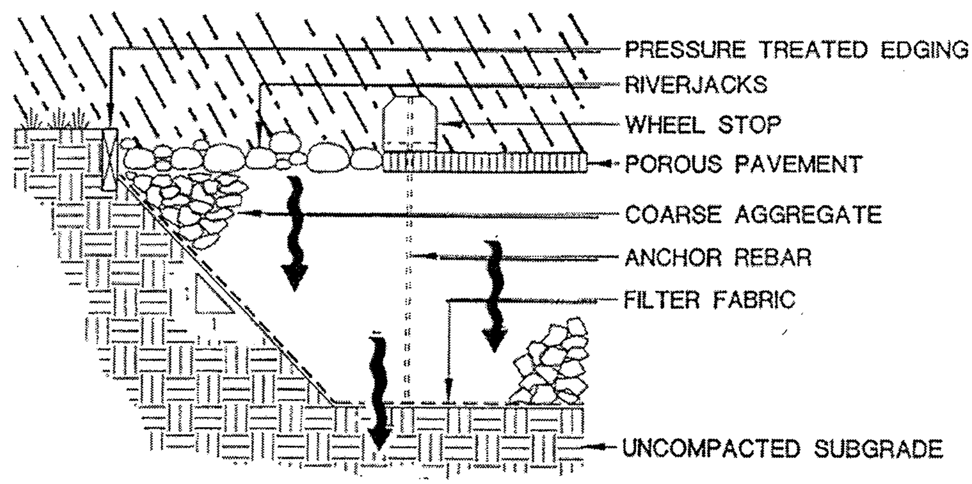

Figure 2 Backup infiltration system for permeable parking lot installations.
Graphic courtesy of Cahill Associates

- To ensure that the asphalt top course is not saturated from high water levels in the aggregate base (as a result of subgrade soil clogging), a positive overflow is usually installed.

Cahill Associates design some systems to infiltrate storm flows from adjacent buildings. Water is collected from roof downspouts, conveyed through a catch basin (to remove debris), and distributed in perforated pipes throughout the storage and infiltration aggregate base.

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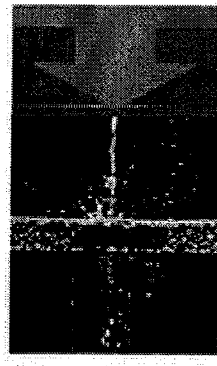
Stormwater

FEATURES



Porous Asphalt Pavement With Recharge Beds: 20 Years & Still Working

With the right soil conditions and careful design, installations retain their ability to infiltrate.

By Michele C. Adams

Is it possible to have a stormwater best management practice (BMP) that reduces impervious areas, recharges groundwater, improves water quality, eliminates the need for detention basins, and provides a useful purpose besides stormwater management? This seems like a lot to expect from any stormwater measure, but porous asphalt pavement on top of recharge beds has a proven track record.

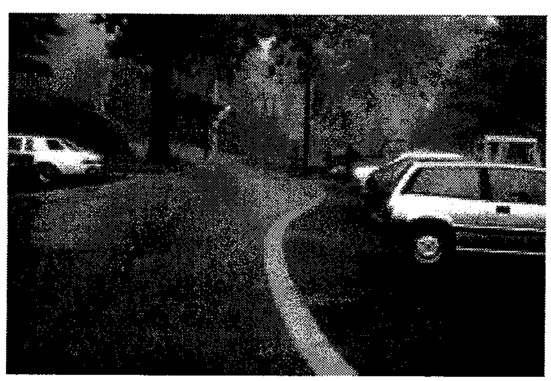


Figure 1. Rainfall runs off traditional impervious asphalt (center drive) but drains through porous asphalt parking spaces.

First developed in the 1970s at the Franklin Institute in Philadelphia, PA, porous asphalt pavement consists of standard bituminous asphalt in which the aggregate fines (particles smaller than 600 µm, or the No. 30 sieve) have been screened and reduced, allowing water to pass through the asphalt (Figure 1). Underneath the pavement is placed a bed of uniformly

Figure 2. Cross-section through porous asphalt showing subsurface infiltration bed beneath

graded and clean-washed aggregate with a void space of 40%. Stormwater drains through the asphalt, is held in the stone bed, and infiltrates slowly into the underlying soil mantle. A layer of geotextile filter fabric separates the stone bed from the underlying soil, preventing the movement of fines into the bed (Figure 2).

Porous pavement is especially well suited for parking-lot areas. Several dozen large, successful porous pavement installations, including some that are now 20 years old, have been developed by Cahill Associates (CA) of West Chester, PA, mainly in Mid-Atlantic states. These systems continue to work quite well as both parking lots and stormwater management systems. In fact, many of these systems have outperformed their conventionally paved counterparts in terms of both parking-lot durability and stormwater management.

Installations Old and New

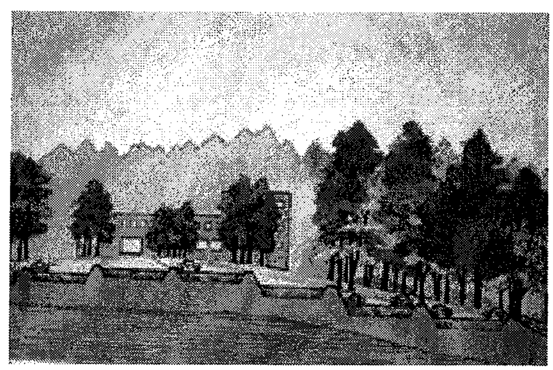


Figure 3. Porous pavement parking bays are benched down a hillside.

One of the first large-scale porous pavement/recharge bed systems that CA designed is in a corporate office park in the suburbs of Philadelphia (East Whiteland Township, Chester County). This particular installation of about 600 parking spaces posed a challenge because of both the sloping topography and the underlying carbonate geology that was prone to sinkhole formation. The site also is immediately adjacent to Valley Creek, designated by Pennsylvania as an Exceptional Value stream where avoiding nonpoint-source pollution is of critical importance. Constructed in 1983 as part of the Shared Medical Systems (now Seimens) world headquarters, the system consists of a series of porous pavement/recharge bed parking bays terraced down the hillside connected by conventionally paved impervious roadways. Both the top and bottom of the beds are level, as shown in Figure 3, hillside notwithstanding. After 20 years, the system continues to function well and has not been repaved. Although the area is naturally prone to sinkholes, far fewer sinkholes have occurred in the porous asphalt areas than in the conventional asphalt areas, which the site manager attributes to the broad and even distribution of stormwater over the large areas under the porous pavement parking bays.

Other early 1980s sites, such as the SmithKline Beecham (now Quest) Laboratory in Montgomery County, PA, and the Chester County Work Release Center in Chester County, PA, also used the system of terracing the porous paved recharge beds down the hillside to overcome the issues of slope. At the DuPont Barley Mills Office complex in Delaware, the porous pavement was installed specifically to avoid the construction of a detention basin, which would have destroyed the last wooded portion of the site. More recently (1997), the porous parking lots at the Penn State Berks Campus were constructed to avoid destroying a wooded campus hillside. The Berks lots, also on carbonate bedrock, replaced an existing detention basin and have not experienced the sinkhole problems that another campus detention basin has suffered.

How It Works

The porous asphalt mix has a lower concentration of fines than traditional asphalt, as shown in Table 1, accomplished by straightforward screening. In all other manufacturing aspects, porous asphalt is the same as conventional asphalt and can be mixed at a standard asphalt batch plant. With fewer fines, the asphalt is porous and allows water to drain though the material through virtually imperceptible openings (to the untrained eye, porous pavement properly prepared is difficult to distinguish from conventional pavement). There are several variations of the mix, including gradations developed by various state transportation departments seeking a pavement that also can be used to reduce noise and skidding. For the purposes of stormwater management, we have found the best performance from the mix indicated in Table 1.

Table 1.
Standard Porous Asphalt Mixes

US Standard Sieve Size	Percent Passing
1/2 in.	100
3/8 in.	95
#4	35
#8	15
#16	10

#30	2
Percent bituminous 5.75-6.0% by weight	

The underlying stone recharge bed consists of a uniformly graded (i.e., screened) 1.5- to 2.5-in. clean-washed stone mix, such as an AASHTO No. 2. Depending on local aggregate availability, both larger and smaller size stones have been used. The important requirement is that the stone be uniformly graded (to maximize void space) and clean washed. The void space between the stones provides the critical storage volume for the stormwater. Stones that are dusty or dirty might clog the infiltration bed and must be avoided. The stone bed is usually between 18 and 36 in. deep, depending on stormwater storage requirements, frost depth considerations, and site grading. This depth provides a significant structural base for the pavement. As a result, porous asphalt exhibits very few of the cracking and pothole formation problems encountered in conventional pavement.

The bottom of the recharge bed is excavated to a level surface and is not compacted. This allows water to distribute and infiltrate evenly over the entire bed bottom area. Compaction of the soils will prevent infiltration, so it is important that care be taken during excavation to prevent this. The bottom of the bed cannot be placed on fill material unless that fill material is stone. A layer of nonwoven geotextile at the bottom of the bed allows the water to drain into the soil while preventing the soil particles from moving into the stone bed.

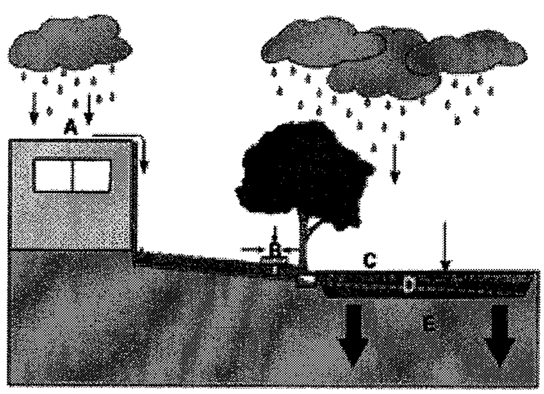


Figure 4. Roof leaders can be connected directly to the subsurface infiltration bed (corresponds to legend below).

A - Precipitation is carried from roof by roof drains to storage beds.
B - Stormwater runoff from impervious areas and lawn areas is carried to storage beds.
C - Precipitation that falls on pervious paving enters storage bed directly.
D - Stone beds with 40% void space store stormwater. Perforated pipes distribute

Very often the underlying stone bed will provide stormwater management for adjacent impervious areas such as roofs and roads. To achieve this, we convey the stormwater directly into the stone bed and then use perforated pipes in the stone bed to distribute the water evenly (Figures 4 and 5).

Design Considerations

In the late 1970s and early 1980s, as we designed our first systems, we were

stormwater from impervious surfaces evenly throughout the beds.
E - Stormwater exfiltrates from storage beds into soil and recharges the groundwater.

Figure 5. Perforated pipes distribute stormwater evenly throughout the infiltration bed.

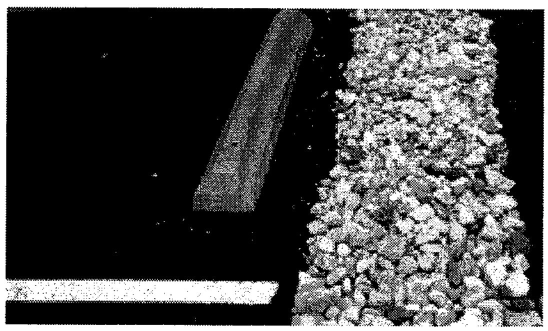


Figure 6. Unpaved stone edge in the event that the surface is repaved.

uncertain how well the porous asphalt would hold up over time and use. In these first systems, such as the one at the Morris Arboretum in Philadelphia (1982), we designed the parking spaces with porous pavement but constructed the aisles and connector roadways with conventional asphalt. However, we extended the stone stormwater storage/infiltration bed under the entire parking area, including the areas with impervious paving.

Over time, we have found that the porous asphalt material has held up as well as, or better than, the conventional asphalt, largely because of the solid sub-base provided by the stone storage/infiltration bed. In subsequent designs we have paved the entire surface in the porous asphalt. We have found that sufficient asphalt content is essential to pavement durability (5.75,6.0% bituminous asphalt by weight). In sites where a lower asphalt content was used, some surface scuffing can be observed on the pavement surface. In different situations, we have tried various commercial additives intended to improve strength or performance in cold weather, but in general we have avoided any proprietary mixes or additives. Porous pavement is not a product but a design technique.

We have also taken the "belt and suspenders" approach to all of our systems. If the pavement were to be paved over, forgotten, or clogged, stormwater still must reach the stone bed below the pavement. Often we have used an unpaved stone edge, as shown in Figure 6, for this purpose. We have also used catch basins that discharge to perforated pipes in the bed.

Additionally, in case the bed bottom clogs (which has not happened yet), we have always designed the underlying bed systems with a "positive overflow." During a storm event, as the water in the underlying stone bed rises, it must never be allowed to saturate the pavement. We have used a catch basin with a higher outlet than inlet to provide positive release. In this way the bed also serves as an "underground detention basin," eliminating the need for a separate basin.

As a design rule, if the stone bed can provide a storage volume equal to the volume of *increased* runoff during a local two-year storm event (that is, the difference in the volume of runoff before development and after development), this will provide sufficient storage to mitigate the peak *rate* of runoff during larger storm events (25- to 100-year). Most local ordinances are concerned with rate of runoff. Essentially the bed acts as an underground detention basin in extreme storm events, albeit one that also reduces volume. A storm can be "routed" through the bed using the same calculation methods employed to route detention basins to confirm peak-rate mitigation.

As a final design consideration, infiltration systems also work best when the water is allowed to infiltrate over a large area. As a rule of thumb, we usually design to a ratio of 5:1 impervious area to infiltration area. That is, the runoff from 5 ac. of impervious area would require a 1-ac. infiltration bed. Because parking tends to consume so much of our landscape relative to other impervious surfaces, meeting this ratio is rarely a problem.

Soil and Subsurface Conditions

Suitable soil conditions are required for infiltration. The designer must evaluate a number of factors, including soil type, infiltration rate, depth to bedrock, and depth to water table. Some of the guidelines we have used in design are shown in Table 2. The most important factor is that the location of the porous pavement infiltration system be considered early in the design process. Traditionally engineers have designed stormwater systems that collect and convey runoff to the lowest point. By the time you have done this, you are likely to be at the wettest location on the site, next to the stream or wetlands or in poor soils. Infiltration systems perform best on upland soils. Some of our more recent designs integrate a mixture of large and small infiltration systems throughout the site, including porous pavement, to avoid conveying stormwater any distance.

Table 2. Design Guidelines for Subsurface Infiltration
• Avoid piping water long distances. Look for infiltration opportunities within the immediate project area. • Consider past uses of site and appropriateness of infiltration design and porous pavement. • Consider the source of runoff. Incorporate sediment reduction techniques as appropriate.

- Perform site tests to determine depth to seasonal high water table, depth to bedrock, and soil conditions, including infiltration capabilities. Design accordingly. Maintain 3 ft. above high water table and 2 ft. above bedrock.
- Avoid excessive earthwork (cut and fill). Design with the contours of the site. Maintain a sufficient soil buffer above bedrock.
- Do not infiltrate on compacted fill.
- Avoid compacting soils during construction.
- Maintain erosion and sediment control measures until site is stabilized. Sedimentation during construction can cause the failure of infiltration systems.
- Spread the infiltration over the largest area feasible. Avoid concentrating too much runoff in one area. A good rule of thumb is 5:1 impervious area to infiltration area (i.e., 5 ac. of impervious area to 1 ac. of infiltration area). A smaller ratio is appropriate in carbonate bedrock areas.
- The bottom of the infiltration area should be level to allow even distribution.
- The surface of the porous pavement should not exceed 5%. Use conventional pavement in steep areas that receive vehicular traffic.
- Provide thorough construction oversight.

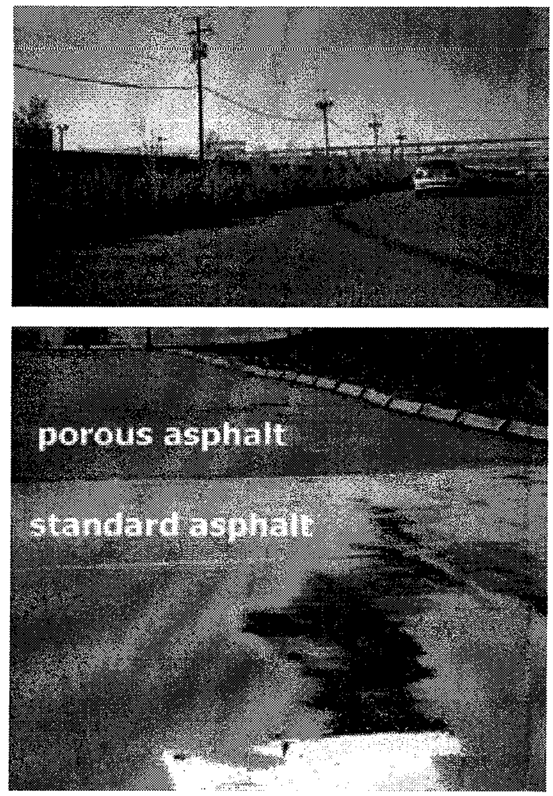
Before any infiltration system is designed, soil investigation must be done. This consists of two steps. First, a simple "deep hole" 6-8 ft. in depth is excavated with a backhoe and the soil conditions are observed. While some designers prefer an auger, we believe that there is no substitute for physically observing and describing the soil horizons. Next, infiltration measurements are performed at the approximate bed bottom location. We have used both simple percolation tests, which are not very scientific, as well as infiltrometer readings. We do not consider infiltration rates between 0.1 and 0.5 in./hr. too slow; rather, this means that infiltration will occur slowly over a two- to three-day period, which is ideal for water-quality improvement.

Underlying geology must also be considered in areas such as those underlain by carbonate formations. In that situation, more detailed site investigation may include borings and ground-penetrating radar. Contrary to popular belief, properly designed infiltration systems do not create sinkholes. A number of our systems, including older systems, are located in carbonate areas. In several situations we have successfully installed porous pavement infiltration systems adjacent to areas where detention basins created sinkholes.

When Infiltration Is Limited

Despite the need for infiltration, not all sites and soils are suitable. In those situations, we have designed porous pavement systems to reduce impervious surfaces or as part of a water-quality improvement program. The porous pavement parking lots recently constructed at the John Heinz National Wildlife Refuge near the Philadelphia Airport are located in a wet, low-lying site that has been subject to fill over the years. The soils are not well drained. In this situation, a trench was excavated to a lower gravel layer to facilitate infiltration, but the parking lots primarily serve to avoid the creation of new impervious surfaces at this valuable wildlife refuge.

At the Ford Motor Company Rouge Facility in Dearborn, MI, the use of porous pavement is an important part of Ford's commitment to sustainability. The original manufacturing plant was constructed in a low-lying wet area and has been subject to a century of industrial use. In 1999, Ford constructed a porous parking lot designed to slowly drain to a series of planted wetland swales (Figures 7 and 8). The stormwater stored in the beds beneath the porous pavement supports the vegetated swales by discharging slowly to the planted areas. The system is specifically designed to improve water quality. Referred to as the "Mustang Lot" (because new Ford Mustangs are parked there after assembly), the lot has worked well, and current Ford plans include the construction of 62 ac. of porous pavement areas that will drain to constructed stormwater wetlands.



Figures 7 & 8. This lot at Ford Motor Company in Detroit is made of porous asphalt that drains stormwater to vegetated bioswales.

Water Quality

There have been limited sampling data on the porous pavement systems, although the available data indicate a very high removal rate for total suspended solids, metals, and oil and grease (Table 3). More recently, Brian Dempsey, Ph.D., and his research assistant, David Swisher, have conducted research at the Pennsylvania State University. Dempsey has been studying a porous pavement system constructed at the Centre

County/Pennsylvania State Visitor Center in 1999, comparing the water quality in the infiltration beds to observed runoff from a nearby impervious parking lot. He has monitored the infiltration rates of this system and found that the system has maintained a consistent infiltration rate. During a 25-year precipitation event, there was no surface discharge from the stone beds.

Table 3
Pollutant Removal Efficiencies for Infiltration BMPs (with porous paving highlighted)

Water-Quality Parameter	Infiltration BMP Type				
	Trench	Trench	Porous Paving	Porous Paving	Average Removal Efficiency
Total Suspended Solids	90%	---	95%	89%	91%
Total Phosphorous	60%	68%	71%	65%	66%
Total Nitrogen	60%	---	---	83%	72%
Total Organic Carbon	90%	---	---	82%	86%
Lead	---	---	50%	98%	74%
Zinc	---	---	62%	99%	81%
Metals	90%	---	---	---	90%
Bacteria	90%	---	---	---	90%
Biochemcial Oxygen Demand	75%	---	---	---	75%
Cadmium	---	---	33%	---	33%
Copper	---	---	42%	---	42%
Total Kjeldahl Nitrogen	---	53%	---	---	53%
Nitrate	---	27%	---	---	27%
Ammonia	---	81%	---	---	81%

Cost

Porous pavement does not cost more than conventional pavement. On a yard-by-yard basis, the asphalt cost is approximately the same as the cost of conventional asphalt. The underlying stone bed is usually more expensive than a conventional compacted sub-base, but this cost difference is generally offset by the significant reduction in stormwater pipes and inlets. Additionally, because porous pavement is designed to "fit into" the topography of a site, there is generally less earthwork and no deep excavations. When the cost savings provided by eliminating the detention basin are considered, porous pavement is always an economically sound choice. On those jobs where unit costs have been compared, the porous pavement always has been the less expensive option. Current jobs are averaging between $2,000 and $2,500 per parking space for parking, aisles, and stormwater management.

Construction

Invariably, when an infiltration BMP fails, it is because of difficulties and mistakes in the design and construction process. This is true for porous pavement and all other infiltration BMPs. Carelessness in compacting the subgrade soils, poor erosion control, and poor-quality materials are all causes of failure. For that reason, we provide detailed specifications on site protection, soil protection, and system installation. On every project, we meet with the contractor before construction and discuss such things as the need to prevent heavy equipment from compacting soils, the need to prevent sediment-laden waters from washing onto the pavement, and the need for clean stone. We verbally review the installation process with the project foreman. During construction, we routinely stop by the site or provide construction advice. Successful installation of any infiltration BMP is a hands-on process that requires an active role for the designer. Although we have prevented failures with this approach, most of the problems we have seen at other infiltration BMPs are a result of construction problems. Often the failure does not lie with the contractor or with poor soils but instead is due to a lack of specific guidance for construction procedures.

Because construction sites are inherently messy places, we often find it best to install the porous pavement and other infiltration BMPs toward the end of the construction period. By doing this, there is less risk of creating problems. On many projects, we will excavate the stone bed area to within 6 in. of the final grade and use the empty bed area as a temporary sediment basin and stormwater structure. Care must be taken to prevent heavy equipment from compacting the soils, but sediment can accumulate. In the later stages of the project, the sediment is removed, the bed is excavated to final grade, and the porous pavement system is installed. This also avoids the need for a separate sediment basin during construction.

Maintenance

We recommend that all porous pavement surfaces be vacuum swept twice per year with an industrial vacuum sweeper.

Unfortunately, like many stormwater maintenance requirements, this advice often is overlooked or forgotten. Fortunately, even without regular maintenance, the systems continue to function (we routinely send graduate students and recent hires out in hurricanes to confirm this).

When runoff is conveyed from adjoining areas or roof surfaces into the bed, we often use a drop inlet box or other structure to reduce the amount of detritus and sediment that is conveyed to the bed. This structure also requires regular removal of sediment and debris.

Deicing and Freezing Issues

One of the most common questions relates to concerns about freezing conditions. Freezing has not been an issue, even in very cold climates. We were quite surprised when the owners of early installations first told us that there was less need to snowplow on the porous pavement surfaces. The underlying stone bed tends to absorb and retain heat so that freezing rain and snow melt faster on the porous pavement. The water drains through the pavement and into the bed below with sufficient void space to prevent any heaving or damage, and the formation of "black ice" is rarely observed. The porous surfaces tend to provide better traction for both pedestrians and vehicles than does conventional pavement. Not a single system has suffered freezing problems.

Obviously the use of sand or gravel for deicing would be detrimental to the porous surface. However, salt may be used, and the surface may be plowed if needed. Most sites have found that light plowing eliminates the need for salt since the remaining snow quickly drains through the asphalt. This has the added benefit of reducing groundwater and soil contamination from deicing salts.

Where It Doesn't Work

Because porous asphalt has reduced fines, it has less shear-strength capability and therefore is not recommended for such situations as airport taxiways or slopes greater than 6%. We have not used the material for roadways, although it has been applied more extensively in Europe. There are also locations where the threat of spills and groundwater contamination is quite real. In those situations (such as truck stops and heavy industrial areas), we have applied systems to treat for water quality (such as filters and wetlands) before any infiltration occurs. The ability to contain spills must also be considered and built into the system. Finally, we have avoided the use of porous asphalt in areas where the pavement is likely to be coated or paved over because of a lack of awareness, such as individual home driveways. In those situations, a system that is not altered easily by the property owner is more appropriate (i.e., an infiltration system under a conventional driveway). "Preventative design" is critical.

Variations on the Theme: Porous Walkways and Playgrounds, Porous Concrete

Figure 9. Swarthmore College uses porous asphalt walking paths.

Figure 10. Porous asphalt playground at Penn New School in Philadelphia.

More recently, we have applied the asphalt to situations such as walkways and playgrounds, including paths at Swarthmore College in Philadelphia (Figure 9), and an urban playground at the Penn New School in Philadelphia (Figure 10). At Swarthmore College, the paths are not part of an infiltration bed but are merely intended to reduce impervious cover. The Penn New School project works to reduce the volume of stormwater discharging to the Philadelphia combined sewer overflow. Both of these applications are "retrofits" in urban areas that were previously paved. Howard Neukrug, head of the Office of Watersheds for the Philadelphia Water Department, describes the Penn New School playground as part of "a vision of moving up and down the sewer [water]shed with urban projects which use the rainwater as an asset to the community through sustainable, aesthetic improvements and environmental education. These efforts enhance water-quality and -quantity issues in our rivers and streams and lead toward the environmental outcome we are all striving forófishable, swimmable, drinkable, and accessible waters."

Additionally, we have been applying the use of porous concrete for both sidewalks and parking areas. Similar to the asphalt, the concrete has performed well in cold-weather climates. Because asphalt is less expensive, it remains our first choice for parking lots, but the porous concrete provides a good alternative where asphalt is not appropriate. At the University of North Carolina in Chapel Hill, two large commuter parking lots have recently been installed using a combination of porous asphalt and porous pavement. The university was specifically interested in comparing the installation and performance of both materials in a southern climate but was also driven by a university commitment to manage stormwater for both volume and quality.

Summary

In many new development projects, two-thirds of the new impervious surfaces are related to the automobile. Lost recharge, depleted groundwater levels, low stream baseflows, eroded streambanks, and degraded water quality all are effects of this extensive paving program. Flood and drought are both worsened by a development program of "sealing the earth's surface." We can put parking lots to work for better stormwater management. There is nothing very exciting about a parking lot, but a parking lot designed to maintain the hydrologic balance that existed before development is worth notice. We believe that porous pavement and other infiltration BMPs are critical to successful watershed programs. It is our hope that others will also find this technology worthwhile.

Guest author Michele C. Adams, P.E., is a principal engineer with Cahill Associates in West Chester, PA.

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Center for Stormwater Technology Evaluation and Verification

Treatment Unit J - Porous Asphalt Pavement

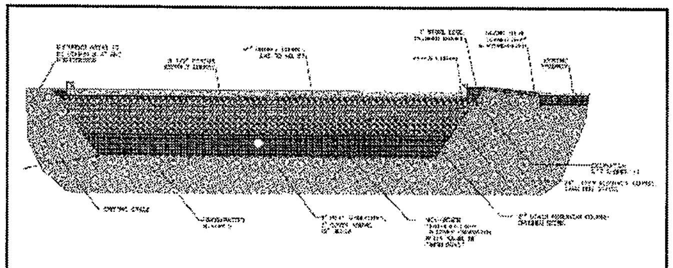
Newly placed porous asphalt pavement being compacted by roller.

Treatment Device Description

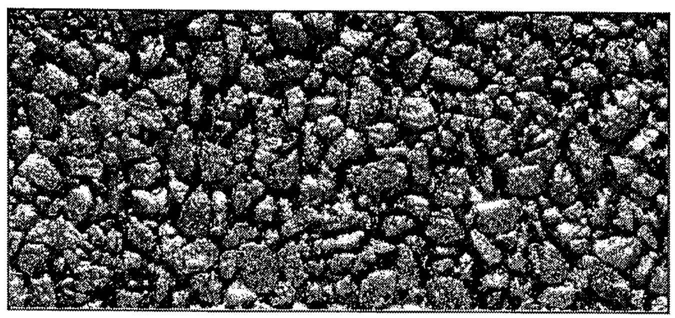
Porous asphalt pavement consists of a permeable asphalt surface placed over a granular working platform on top of a stone reservoir and optional underdrain. The asphalt surface is made permeable by designing it as a 3.5-inch layer of open-graded friction course. Porous asphalt uses a coarser gradation of aggregate and sometimes a stiffer asphalt binder than conventional hot mix asphalt, but is constructed in much the same way. For this parking lot, a standard binder was used. A stone edge is placed outside the curbing to prevent sediment-laden stormwater from entering and clogging the porous asphalt pavement. The granular working platform consists of four inches of AASHTO No. 57 stone. The 24-inch upper reservoir course consists of 'bank run gravel', a well graded sand and gravel mix that filters and detains stormwater through storage in pore spaces. Below this layer is a 21-inch crushed gravel layer with a 6-inch underdrain. The underdrain is elevated 12 inches from the base of the facility to allow for storage and infiltration of approximately 4 inches of water. This water will infiltrate and recharge groundwater during interstorm periods. The base and edges of the subsurface reservoir are lined with non-woven geotextile fabric to prevent migration of fines into the facility. Anticipated maintenance consists of occasional street vacuuming to remove sediments from pores.

WQ Treatment and Stormwater Benefits

Porous asphalt pavement can provide onsite stormwater management with no additional use of space. Properly designed and constructed,these facilities can provide runoff detention, enhanced infiltration and groundwater recharge, and improve water quality. When the facility has had adequate time to infiltrate before a storm, it can provide water quality treatment for at least a four inch rain event. This occurs through filtration in the sand and gravel, and physical settling of remaining solids in the uniformly graded crushed gravel reservoir. Water below the underdrain infiltrates into the subgrade. Rain events larger than four inches are bypassed through the underdrain and into a vegetated swale.



Section



Porous asphalt with approximately 20 percent void space.

Fact Sheet

Category Type:
Porous Pavement, Infiltration

BMP Type:
Low Impact Design

Design Source:
Vermont AOT
National Asphalt Pavement Association (NAPA),
Cahill Associates

Basic Dimensions:
60 ft x 85 ft (approx.)

Specifications:
Catchment: 0.1 acre
Treatment Volume: 1,785 cf
(4 watershed inches)

Treatment Function:
Physical Chemical and Filtration

UNH Environmental Research Group
Center for Stormwater Technology Evaluation and Verification

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Appendix 7 Permeable Paving Research: Infiltration Performance Over Time and Maintenance Strategies

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Porous Asphalt				
Fwa, T.F., Tan, S.A., & Guwe, Y.K. (1999). Laboratory evaluation of clogging potential of porous asphalt mixtures (Paper No. 99-0087). In *Transportation Research Record: Journal of the Transportation Research Board.* No. 1681, pp. 43-49.	Laboratory	Soil was washed into four different porous asphalt mixtures. Permeability (K) was measured after each clogging attempt until the change in permeability was negligible.	Mix 1: initial K = 300.88 in/hr terminal K = 22.00 in/hr Mix 2: initial K = 820.22 in/hr terminal K = 457.20 in/hr	Analysis utilized falling head test that increases infiltration rates; however, rates for optimum mixes far exceed any design storm infiltration need. All mixes currently used on Singapore roadways are apparently used as a topcoat application.
Wei, I.W. (1986). *Installation and evaluation of permeable pavement at Walden Pond State Reservation – Final report.* Report to the Commonwealth of Massachusetts, Division of Water Pollution Control (Research Project 77-12 & 80-22). Boston, MA: Northeastern University, Department of Civil Engineering.	Field evaluation of Walden Pond State Park parking lot in Massachusetts.	Various asphalt mixes were installed in different locations in the new parking lot and evaluated for infiltration rates using sprinkler systems and collection wells.	Best performing mixes: 1978 / 1980 / 1981 K mix: 40 in/hr, 38 in/hr, 37 in/hr J3 mix: 28 in/hr, 4 in/hr, 13 in/hr	Test plots were exposed to traffic, but not the heaviest loads in the overall parking area. No maintenance program.
St. John, M.S., & Horner, R.R. (1997). *Effect of road shoulder treatments on highway runoff quality and quantity.* Seattle, WA: Washington State Transportation Center (TRAC).	Field evaluation of road shoulder treatments in Washington state.	Three types of road shoulder treatments (conventional asphalt, gravel, and porous asphalt) were installed on a heavily traveled two-lane road. Flow-weighted composite samples were collected and runoff quality and quantity was evaluated.	After one year of use the porous asphalt shoulders showed no signs of clogging and had an average infiltration rate of 1750 in/hr.	During the year of monitoring approximately 4.2 ft^3 of sand was applied per test section length for routine sanding operations. No maintenance program reported for the porous asphalt shoulders.
Cahill, Thomas, Cahill Associates. Personal communication, April, 2003.	Interview Tom Cahill concerning their porous asphalt installations.	Cahill Associates has installed approximately 80 porous asphalt surfaces (mostly parking lots and recreation facilities) over the past 20 years. Visual inspections are conducted during rain events.	Visual inspections indicate no failures of any installations and Cahill estimates that oldest surfaces are functioning at 80% of initial capacity.	Cahill stresses that proper installation and strict sediment control are critical. Cahill installations use a perimeter infiltration gallery (hydrologically connected to storage under paved surface) as a backup if asphalt infiltration rate is degraded.
Hossain, M., Scofield, L.A., & Meier, W.R. (1992). Porous pavement for control of highway runoff in Arizona: Performance to date. In *Transportation Research Record No. 1354*, Transportation Research Board, National Research Council, Washington, D.C., pp. 45-54.	Field evaluation near Phoenix, Arizona.	Structural integrity and permeability were evaluated for a 3,500 ft-long porous pavement test section installed on the three northbound lanes of Arizona State Route 87 near Phoenix.	• Initial permeability (1986): 100 in/hr. • After 5 years of service (1990): 28 in/hr.	The porous asphalt has performed well in a heavy traffic (highway) application with "no cracking or significant surface deformation having occurred during the 5 years of service."

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Permeable Pavers				
Borgwardt, S. (1994). *Expert Opinion.* Hannover, Germany: University of Hannover, Institute for Planning Green Spaces and for Landscape Architecture.	Field evaluation of two train station parking lots in Europe. One lot was two years old and the other five years old.	Sprinklers applied simulated rainfall on test section and measured infiltration utilizing infiltrometer (double ring method). Infiltration rates at 60 minutes are used to represent saturated conditions. Grain size distribution was evaluated to correlate paver design with infiltration rate.	• 2-yr old lot: infiltration rate = 2.84 in/hr after 60-min sprinkling. • 5-yr old lot: infiltration rate = 5.70 in/hr after 60-min. of sprinkling.	Higher infiltration rate for the older as compared to the newer installation likely due to application of sand on top of gravel in drainage openings and fines introduced from inadequately washed aggregate base material in newer parking lot. No reported maintenance program.
Smith, D.R. (2000). *Permeable interlocking concrete pavements: Selection, design, construction, maintenance.* Washington, D.C.: Interlocking Concrete Pavement Institute.	Literature review.	Design, construction, maintenance, and infiltration capacity guidelines developed by the Institute's technical committee from literature review.	Smith recommends 1.1-in/hr infiltration rate and a CN of 65 (all soil types) for permeable interlocking concrete pavements. Infiltration rate is for a 20-year life span.	
Borgwardt, S. (1997 February). Performance and fields of application for permeable paving systems. *Concrete Precasting Plant and Technology*, pp. 100-104.	Field evaluation of various driving surfaces in Europe.	Several permeable driving surfaces of various ages were evaluated using a drip infiltrometer.	Reports a durable infiltration rate of 4.25 in/hr.	No reported maintenance programs.
Pratt, C.J., Mantle, D.G., & Schofield, P.A. (1989). Urban stormwater reduction and quality improvement through the use of permeable pavements. *Water Science and Technology, 21*, pp. 769-778.	Field evaluation of experimental plots.	A 4.6m-wide by 40m-long by 350mm-deep (on average) parking area was excavated and divided into 4 trial areas. Each trial area was filled with a different type base aggregate and water quality and quantity measurements taken from under-drains. The wearing course was cement paving blocks and plots were lined with an impermeable membrane.	Three periods were measured during 30 days with a total rainfall of 80.5mm. The 350mm of various sub-base stone and pavers reduced the following amounts of the total precipitation: • Granite: 25% • Limestone: 39% • Blast furnace slag: 45% • Gravel: 37%	

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Brattebo, B.O., Booth, D.B. (2003, November). *Long-term stormwater quantity and quality performance of permeable pavement systems.* Water Research, 37, 4368-4376.	Field evaluation in Puget Sound.	Two plastic grid systems (1 filled with soil and grass and 1 with gravel), a concrete block lattice filled with soil and grass, and concrete blocks with gravel filled cells were installed in a parking lot in the city of Renton, WA. Each stall was evaluated for infiltration capability, infiltrate water quality, and durability. Two parking stalls with each type of permeable paving material and a conventional asphalt stall, for a control, were installed in 1996.	Surface runoff was measured throughout Nov. 2001 and from Jan. to early March 2002. Total rainfall during the collection period was 570mm delivered in 15 distinct precipitation events. The most intense storm event delivered 121mm of rain in 72 hours. The permeable stalls infiltrated virtually all stormwater. Surface runoff occurred for 6 events (other measurable surface runoff was detected, but attributed to leaks in the system). The most significant runoff volume of the 6 events was 4mm during the largest storm noted above (3% of total precipitation).	The permeable parking facility was monitored for the first year following construction. This study is a follow up to that work. The parking stalls were used constantly during the 6 years previous to this monitoring cycle. None of the permeable paving surfaces showed signs of major wear.
Dierkes, C., Kuhlmann, L., Kandasamy, J., & Angelis, G. (2002, September). Pollution retention capability and maintenance of permeable pavements. In *"Global solutions for urban drainage", Proceedings of the Ninth International Conference on Urban Drainage.* Portland, OR.	Field evaluation.	The infiltration rate of a parking stall in a 15-year old permeable paver installation in a shopping center was determined. The stall was then excavated to examine contaminant levels in the underlying base aggregate and soil. Stall was selected with high content of spilled oil on surface. A drip infiltrometer was used to measure infiltration rates.	The paving structure consisted of: pavers with 1-3 mm joints, 5-8 cm thick bedding material (2-5 mm), and a 20-25 cm base of crushed stone (8-45 mm). Infiltration rate: 440 liters/second/hectare in the central region of the stall and 2000l iters/second/hectare at the edges of the stall.	
Clausen, J.C., & Gilbert, J.K. (2003, September). *Annual report: Jordan Cove urban watershed section 319 national monitoring program project.* Storrs-Mansfield, CT: University of Connecticut, College of Agriculture and Natural Resources.	Field evaluation in southeastern Connecticut.	Two conventional asphalt, two conventional crushed aggregate, and two permeable paver (UNI group Eco-Stone) driveways were monitored during a 12-month period for runoff, infiltration rate, and pollutant discharge. Trench drains at the bottom of the driveways with tipping buckets measured runoff volume. Infiltration rates were assessed using 2 methods: a single ring infiltrometer and a perforated hose for a flowing test. Contributing area for each driveway and land cover type (roof, lawn, etc.) was assessed.	Infiltration rates for the permeable pavers: • Infiltrometer 2002: 7.7 in/hr. • Infiltrometer 2003: 6.0 in/hr. • Flowing infiltration 2003: 8.1 in/hr. • Runoff coefficient for pavers (runoff depth/rainfall depth) = 24%.	No maintenance program reported. The Eco-Stone driveways were two years old at the time of the study.

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Pervious Concrete				
Wingerter, R., & Paine, J.E. (1989). *Field performance investigation: Portland Cement Pervious Pavement.* Orlando, FL: Florida Concrete and Products Association.	Laboratory and field evaluation in Florida.	Test slabs of pervious concrete were poured, 18" cores removed, and infiltration rates tested. Cores were then clogged by adding 2" of sand and pressure washing for 1.5 hrs. Existing porous concrete installations were also evaluated by coring and measuring infiltration rates and percent of void space infiltrated by fines.	Laboratory core • Pre-clogging infiltration rate = 23.97 in/min. • Post-clogging infiltration rate with 1" sand remaining on surface = 3.66 in/min and 10.22in/min with sand removed from surface. Field tests • Naples FL restaurant parking lot 6.5 yrs. old: infiltration rate = 4 in/min, 3.4% infiltrated by fines. • Fort Myers parking area 8 yrs. old: infiltration rate = 7 in/min, 0.16% infiltrated by fines.	Analysis utilized falling head test that increases infiltration rates, however, rates far exceed any design storm infiltration need. No reported maintenance programs.
Maintenance				
Balades, J.D., Legret, M., & Madiec, H. (1995). Permeable pavements: Pollution management tools. *Water Science and Technology, 32,* 49-56.	Field evaluation in France.	Various street cleaning techniques were applied to different permeable pavements, including parking lots and roads with heavy traffic. Infiltration rates measured before and after cleaning.	Sweeping followed by suction: • Highly clogged surfaces (< 14 in/hr) no improvement. • Partially clogged surfaces (112–140 in/hr) original infiltration rates (210.60–224.64 in/hr) were obtained after two passes. Suction only • 1st site: initial infiltration rate = 7.02 in/hr, after two passes infiltration rate = 28.08 in/hr. • 2nd site: initial infiltration rate = 210.60 in/hr, after two passes infiltration rate = 280.80 in/hr. High pressure wash with suction • Shopping mall: initial infiltration rate = 9.83 in/hr (parking area) and 28 in/hr (roadway), after two passes infiltration rates = 84.24 in/hr for both parking and roadway. • Residential road: initial infiltration = approximately 0 in/hr, after treatment infiltration rate = 112 in/hr.	The analysis does suggest that restoring a percentage or all of the initial infiltration rate of a permeable pavement installation is possible. However, the type of permeable surface and the cleaning technique applied to that specific surface was not reported.

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Gerrits, C., & James, W. (2001). *Restoration of infiltration capacity of permeable pavers.* Master's thesis, University of Guelph. Guelph, Ontario, Canada.	Field evaluation of pervious paver (Eco-Stone) parking lot surfaces at University of Guelph in Ontario.	110 9m x 9m plots in the parking lot were tested for infiltration rates. Material in the drainage cells was excavated to various depths and tests repeated to evaluate regenerating infiltration capacity. Plots were categorized by low, medium and high average daily traffic, and paver bedding material. Parking lot was approximately 8 years old at time of research. Lot is sanded and plowed for snow during winter.	• 3" gravel bed: low traffic: initial = 5.85 in/hr excavate 20 mm = 7.8 in/hr med traffic: initial = 0.58 in/hr excavate 20 mm = 7.80 in/hr • 4" sand bed: low traffic: initial = 0.35 in/hr excavate 20 mm = 0.94 in/hr med traffic: initial = 0.12 in/hr excavate 20mm = no change	Authors find that vacuuming upper 5-20 mm of drainage cell material can regenerate infiltration, and that amounts of material removed to improve infiltration rates can be achieved by modern street sweeping equipment. Sand bed with high traffic most difficult to regenerate and medium traffic with gravel bed easiest to regenerate. Areas with pine needles and vegetation on drainage cells had higher infiltration rates than plots without vegetation material.
Dierkes, C., Kuhlmann, L., Kandasamy, J., & Angelis, G. (2002, September). Pollution retention capability and maintenance of permeable pavements. In *"Global solutions for urban drainage", Proceedings of the Ninth International Conference on Urban Drainage.* Portland, OR.	Field evaluation.	A high-pressure wash and vacuum street cleaning machine was used to clean a school yard permeable paver installation (approximately 4 yr old). The pavers were 10 cm x 20 cm x 8 cm installed on a 2-5 mm pea gravel leveling layer, and the joints filled with 1-3 mm basalt aggregate. Infiltration rates before and after cleaning were evaluated using a drip infiltrometer.	• Infiltration rate before cleaning at 3 selected points: less than 1 mm/second/hectare. • Infiltration rates after cleaning at same 3 points: 1545-5276 liters/second/hectare.	

Green Roofs

The following excerpt is from http://www.wbdg.org/design/greenroofs.php:

> Green roofs, also known as vegetated roof covers or eco-roofs, are thin layers of living vegetation installed on top of conventional flat or sloping roofs. Green roofs protect conventional roof waterproofing systems while adding a wide range of ecological and aesthetic benefits. They are a powerful tool in combating the adverse impacts of land development and the loss of open space.
>
> Green roofs are divided into two categories: 1) extensive green roofs, which are 6 inches or shallower and are frequently designed to satisfy specific engineering and performance goals, and 2) intensive green roofs, which may become quite deep and merge into more familiar on-structure plaza landscapes with promenades, lawn, large perennial plants, and trees. This guide addresses only the more shallow extensive green roofs.
> The challenge in designing extensive green roofs is to replicate many of the benefits of green open space, while keeping them light and affordable. Thus, the new generation of green roofs relies on a marriage of the sciences of horticulture, waterproofing, and engineering.
>
> The most common vegetated roof cover in temperate climates is a single un-irrigated 3- to 4-inch layer of lightweight growth media vegetated with succulent plants and herbs. In Germany, this simple design has demonstrated the highest benefit-to-cost ratio. In most climates, a properly designed 3-inch deep vegetated roof cover will provide a durable, low maintenance system that can realize the many benefits that green roofs have to offer.

Figure 1. Heinz 57 Center, Pittsburgh, PA (2001)

Green Roof Systems Description

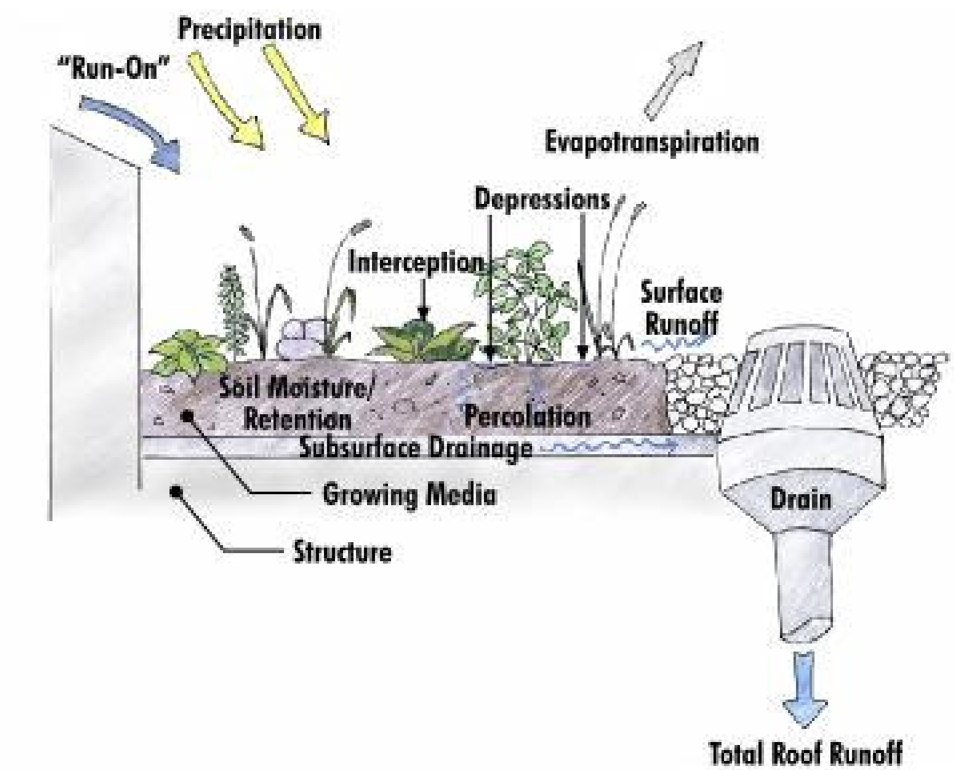
Green roof systems that are from 2 to 8 inches thick are called "extensive" green roofs. Typical extensive green roofs are constructed as layered systems, as shown below. The bottom layer is a waterproof membrane that is installed onto the roof deck. Roof insulation may be placed either above or below the waterproof membrane, depending on the architectural roof design for the project. A root barrier is typically installed as the next layer to reduce the chance of root penetrations into the waterproof membrane. A drainage layer is then placed that promotes free drainage, collecting seepage from the green roof and conveying it to the roof drain. The drainage layer is usually either a fabricated drainage product or a layer of sand to gravel size aggregate with high hydraulic conductivity. Light-weight aggregates such as expanded slate or pumice are often used to reduce roof loads. A geotextile is usually placed on aggregate drainage systems to prevent migration of fines from the growing media into the drainage layer.

The shallow profile of an extensive green roof reduces the weight of the system, but also limits moisture available for plants. The added weight of an extensive green roof is an insignificant load for many types of buildings, especially if it is known early in the design. While green roofs cost more than a conventional roof initially, life cycle costs savings associated with the benefits they offer have been shown to offset initial outlays over the life of a roof. These aspects make extensive green roofs a versatile practice.

Extensive green roofs are often planted with drought resistant, shallow rooted plants, particularly sedums and succulents. More varieties of plants can be used if an irrigation system is provided. Extensive green roofs 8 inches thick provide adequate rooting depth for herbs and vegetables (not root crops).

Green roofs over 8 inches thick are called “intensive”. Intensive green roofs are of sufficient weight that the practice must be accounted for in the structural design, which may increase the structure cost. Intensive green roofs enable sophisticated planting schemes using a variety of plants, including shrubs and deep rooted vegetation that would not survive in a shallower green roof profile. Intensive green roofs require more planning and stronger structures.

The growing medium is the heart of a green roof system since it comprises most of the volume of the green roof “veneer”, enables plants to grow and survive harsh rooftop conditions, and provides substantial stormwater benefits. Growing media are engineered “soils” that are designed to achieve specific goals for rainwater retention and provide appropriate growing conditions for the green roof vegetation. The depth of the media depends on the desired functions for the green roof, the load bearing capacity of the structure, desired plants, and costs.



Typical Green Roof Section and Hydrologic Processes
Source: Taylor and Gangnes, 2004

Most growing media mix designs consist of primarily mineral aggregates with small amounts of organic material. The media is mostly mineral because organic soil materials installed in green roofs tend to decompose and dissipate over time. Light-weight aggregates such as expanded slate or pumice are often incorporated to reduce roof loads. Hydraulic qualities that enable plantings to establish and survive the harsh rooftop environment are a primary consideration in the growing media design, such as the resistance to moisture removal as the media dries, which can be configured to facilitate the vegetation adapting to dry roof conditions (Miller, 2003). Miller (2003) noted that:

> *The ideal green roof media will combine many features that are typically mutually exclusive in nature:*
>
> - *Efficiently absorb and tenaciously retain water*
> - *Be readily drained*
> - *Offer a high void ratio (air volume), even when approaching saturation*
> - *Exhibit moderate to high effective surface area*
>
> *As a result green roof media is almost always a manufactured 'soil-less' material.*

The growing media is planted with species suitable to rooftop environs. Plants are typically drought and wind tolerant to accommodate the exposed setting. Plants that can thrive in nutrient-poor shallow substrates are most suitable. The Sedum family of plants has proven especially well-suited for green roofs.

Additional components may be included as part of the green roof assembly but are not always required. Irrigation systems may be needed depending on the planting scheme. Erosion control fabrics are used to prevent the media from eroding until plant coverage and root structure is adequate to prevent movement of the growing media material. On sloped roofs, baffles may be employed to prevent the media from migrating (sliding) down the roof. On high roofs, steel cables or nets may be integrated to hold the green roof in place during high winds.

Green Roof Hydrologic Processes

The veneer of growing media and plants affect the hydrologic cycle of buildings with green roofs. The green roof plants absorb moisture from the soil and transpire water to the atmosphere. The growing media absorbs and retains moisture. Excess moisture that is not retained in the growing media percolates through the media, and then flows through the drainage layer to the roof drain, after which point the flow becomes building runoff. The net effect is that initial portions of rainfall are retained until the moisture retaining capacity of the growing media is satisfied, upon which point "breakthrough" occurs and water begins to seep through from the media into the drainage layer.

It is worth noting that for typical green roofs - that are designed using engineered growing media – excess precipitation almost always becomes seepage flow through the media rather than surface "runoff". The percolation and lateral flow of the seepage flow extends the time for rain to become runoff, when compared to a conventional roof, attenuating the flow of runoff from the building.

Green Roof Design Principles & Benefits

The following excerpt is from http://www.wbdg.org/design/greenroofs.php:

A. Features

All well-designed green roofs include subsystems responsible for:

- ***Drainage:*** Green roof drainage design must both maintain optimum growing conditions in the growth medium and manage heavy rainfall without sustaining damage due to erosion or ponding of water
- ***Plant nourishment and support:*** The engineered medium must meet exacting requirements for grain-size distribution, void ratio, moisture retention, etc. and
- ***Protection of underlying waterproofing systems:*** Green roof assemblies must protect the underlying waterproofing system from human activities (including the impact of maintenance) and biological attack.

A wide range of methods can achieve these functions. For instance, drainage layers may consist of plastic sheets, fabric or synthetic mats, or granular mineral layers. Similarly, the physical properties and performance characteristics of growing media (engineered soils) and plant materials may vary with the climate, plant community, or engineering requirements. Figure 2 shows a generic cut-away of a common type of green roof assembly that utilizes a lower granular drainage layer in combination with an upper growth medium or substrate.

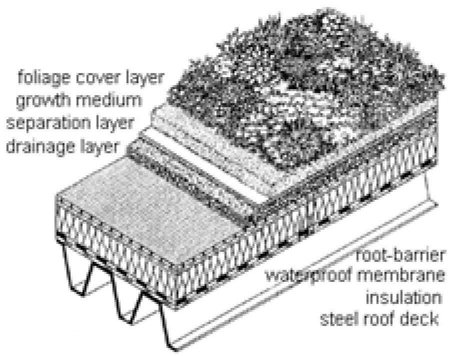


Figure 2. Generic Extensive Green Roof
Courtesy of Optigrün Intl. AG

The selection of a particular approach may depend on performance-related considerations, such as runoff control, drought-tolerance, biodiversity, appearance or accessibility to the public. While many pre-engineered systems are currently available, it is frequently necessary to customize these systems to satisfy specific performance objectives.

B. Ancillary Features

1. Waterproofing

Many premium waterproofing materials have a proven track record when used in combination with green roof installations. These include, but are not limited to polyvinyl chloride (PVC), thermal polyolefin, EPDM rubber, polymer modified bituminous sheet membranes (e.g., SBS membrane), liquid-applied rubberized-asphalt, and coal tar pitch. Other materials are likely to enter the industry as their suitability is proven in certification testing and prototype installations.

Worldwide, polymer modified bituminous membranes and PVCs are the most common. Many of these installations have now been in place for over 30 years and continue to perform as designed.

In all instances, materials, methods of installation, and quality assurance procedures must be more stringent when green roof installation is involved. **Waterproofing material that cannot withstand decades of root and biological attack unaided must be protected with a supplemental root-barrier layer.** For information and standards pertaining to waterproofing materials, consult the National Roofing Contractors Association (NRCA) or American Standard Testing Methods (ASTM).

2. Pitched Roof Installations

To install extensive vegetated roof covers on pitches steeper than 2.5:12 (12 degrees) supplemental measures will be required to prevent sliding instability. Varied building systems have been developed to support vegetated covers on steeply pitched roofs. Pitched roof systems merge into vertical facade greening techniques.

Figure 3. Life Expression Wellness Center, Sugar Loaf, Pennsylvania (2001)

3. Wind Resistance Systems

Due to the unique physics of the green roof profile, attaching the elements of the green roof to the underlying structure is not usually important. The biomass bonds with the fabrics to create a unified cover, and the plants themselves create enough surface wind turbulence to foil potential uplift—the converse of an airfoil. If the green roof will be located in an unusually-high wind area, such as a high-rise building or a coastal region, appropriate ballasts should be specified. Guidelines for ballast requirements are available from European green roof providers.

4. Modular Systems

Modular systems involve installing the green roof system inside plastic trays. Use of these systems does not relieve the designer from responsibility for considering the integrity of the underlying waterproofing system, nor does it make location of damaged waterproofing easier. However, these systems can be useful when designing small gardens on residential property or terraced commercial roofs. They also preserve flexibility to re-arrange landscape designs in the future. Owners who wish to engage in active gardening will find modules a convenient way to do this without damage to their homes' waterproofing. Two companies in North America currently offer modular, or tray, components, GreenTech and Weston/ABC Supply.

5. Electric Leak Detection

Inexpensive methods for locating damaged waterproofing underneath vegetated covers are available. These include the electric field vector mapping (EFVM) procedure. This method works by charging the moist media layer of the green roof with electricity and then looking for electrical grounds caused by moisture in contact with an underlying steel or concrete deck structure.

C. Benefits

There are many potential benefits associated with green roofs. These include:

- Controlling storm water runoff
- Improving water quality
- Mitigating urban heat-island effects
- Prolonging the service life of roofing materials

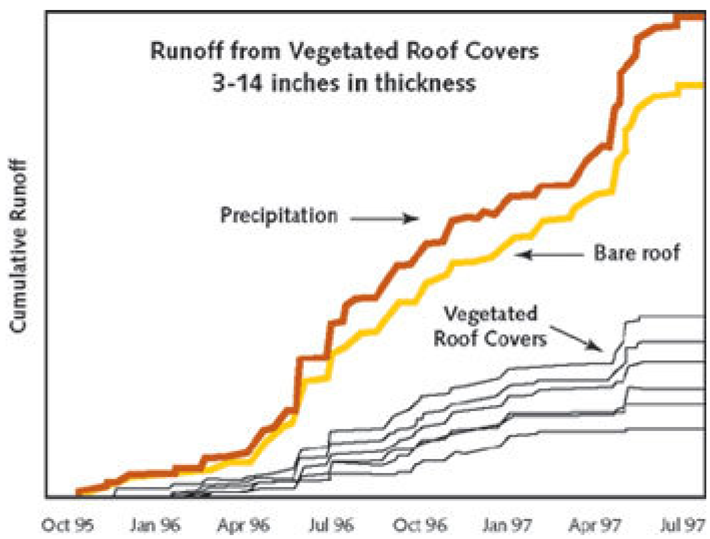
- Conserving energy
- Reducing sound reflection and transmission
- Creating wildlife habitat, and
- Improving the aesthetic environment in both work and home settings.

As a result green roofs may be appropriate as an addition to many types of buildings, including commercial, industrial, institutional, and residential settings.

1. Controlling Storm Water Runoff

The rapid runoff of storm water from paved areas and roofs contributes to destructive flooding, erosion, pollution, and habitat destruction. The capacity of green roofs to moderate this runoff through both retention (water holding) and detention (flow-slowing) properties has been well-documented in Europe and increasingly in the United States. Green roofs share many engineering features with conventional storm water management basins, and compared to many at-grade storm water management practices, vegetated roof covers are unobtrusive, low maintenance, and reliable. Green roofs may offer the only practical "at-source" technique for controlling runoff in areas that already are highly urbanized.

Vegetated roof covers are particularly effective at controlling runoff on the large roofs typical of commercial and institutional buildings. *They can be designed to achieve specified levels of storm water runoff control, including reductions in both total annual runoff volume (reductions of 50 to 60 percent are common) and peak runoff rates for storms.*



Sample run-off reduction chart.

Reliable techniques for predicting the rate and quantity of runoff from vegetated roof covers have been used successfully to design integrated storm water management measures in Germany, where large zero-discharge developments that rely heavily on green roofs are already operating. For example, the Bondorf transportation center in Sindelfingen achieves net zero storm water runoff discharge, largely through the use of 516,000 square feet (11.8 acres) of green roofs.

2. Improving Water Quality

By reducing both the volume and the rate of storm water runoff, green roofs benefit cities with combined sewer overflow (CSO) impacts. In cities with combined storm and waste water sewer systems, storm water dilutes the sanitary waste water, rendering treatment less efficient. During heavy rainfalls these systems also overflow, discharging raw sewage mixed with runoff into the receiving streams-resulting in ecological damage and human health hazards. Therefore, important water quality benefits are achieved by controlling runoff.

In addition, in urban areas, up to 30% of total nitrogen and total phosphorus released into receiving streams is derived from dust that accumulates on rooftops. Acting as natural bio-filtration devices, green roofs reduce this water contamination. In the Potsdamer Platz district of Berlin, extensive green roofs have been employed on a large scale in an effort to reduce pollution of the River Spree. *This program has demonstrated that extensive green roofs can achieve large reductions in nutrient releases from roofs; however, the research also shows that the correct choices of growing medium and plant types are essential for success.*

3. Mitigating Urban Heat-Island Effects

Covering dark conventional roofs with green roofs can significantly reduce the temperature above the roof. *Green roofs have been shown to out-perform white or reflective roof surfaces in reducing the ambient air temperature.* If sufficient urban surfaces are covered, this cooling (and attendant improvement of air quality) can have significant positive effects on human health, especially for the young and elderly in congested urban areas.

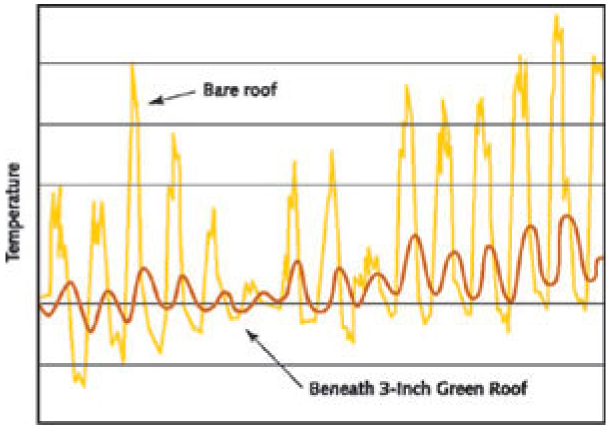
4. Prolonging the Service Life of Roofing Materials

Thirty-five years of experience with green roofs in Germany have demonstrated their value in protecting waterproofing materials. The multiple layers of the green roof protect the underlying roof materials from the elements in three ways: by protecting from mechanical damage (mostly from humans, but also from wind-blown dust and debris, and animals); by shielding from ultraviolet radiation; and by buffering temperature extremes, minimizing damage from the daily expansion and contraction of the roof materials.

A roof assembly that is covered with a green roof can be expected to outlast a comparable roof without a green roof by a factor of at least two, and often three. Although modern green roof systems have not yet been in place longer than 35 years, many researchers expect that these installations will last 50 years and longer before they require significant repair or replacement. For a building owner with a long-term investment in the roofing system, this benefit factor goes a long way toward paying back the initial investment in a green roof.

5. Conserving Energy

Not all benefits will be equally important in every project or climate. For instance, the capacity of green roofs to reduce heat flow, and therefore energy demand in buildings, is mostly a warm season phenomenon. As a result, this benefit will be realized most fully in warm climates, where energy expenditures on air conditioning are an important concern. Energy-related benefits will also be less important in multi-story buildings, due to the low ratio of roof area to the total of exposed building skin. *Because green roofs are more complex than simple insulators, project-specific building envelope analysis is required to predict energy conservation under specific project conditions.*



Comparative temperature chart

6. Reducing Sound Reflection and Transmission

Green roofs can absorb a portion of the sound that otherwise bounces off hard roofing surfaces At the Frankfurt International Airport, green roofs were employed successfully as a means of sound abatement along new runway approaches. *A simple 3-inch deep vegetative cover can be expected to reduce sound transmission by a minimum of 5 decibels. Sound abatement of up to 46 decibels has been measured on thicker roofs.*

7. Creating Wildlife Habitat

Green roofs can be used to create wildlife habitats to supplement or replace diminishing open space in developing areas. With thoughtful planting and avoiding pesticides, *a mature, self-sustaining ecosystem* will teem with insects, spiders, snails, and songbirds. Using native species can recreate lost prairies, as at the Oaklyn Branch Library in Indiana.

8. Improving the Aesthetic Environment

Green roofs offer interesting new opportunities for architectural design. A green roof can allow a structure to merge with the surrounding landscape, provide a dramatic accent, or reinforce the defining aspects of the structure's geometry. In Germany—and increasingly in the United States—green roofs are frequently integrated into the design of hospitals and care facilities in order to provide a more restful and restorative environment for patients. Similarly, multi-unit residences and hotels will find that green roof-tops views substantially enhance property values. In commercial settings, job satisfaction and effectiveness can be enhanced by providing window views of meadows or flower beds or relaxing garden areas for breaks or meetings.

Figure 4. Epworth Retirement Home, Tyrone, Pennsylvania (2000).

APPLICATIONS

A. Design Factors

There are many interactive factors that green roof designer must take into account, balancing many considerations for optimal performance in each setting, including:

- Climate, especially temperature and rainfall patterns
- Strength of the supporting structure
- Size, slope, height, and directional orientation of the roof
- Type of underlying waterproofing
- Drainage elements, such as drains, scuppers, buried conduits, and drain sheets
- Accessibility and intended use
- Visibility, compatibility with architecture, and owner's aesthetic preferences
- Fit with other "green" systems, such as solar panels
- Cost of materials and labor

B. Integration With Other Green Design

Green roofs can be designed in conjunction with solar panels and also work very well in combination with other 'low-impact' development measures, such as infiltration beds, rain gardens, bioretention systems, cisterns and rain barrels. It is common place in Germany to find large developments that have *zero runoff discharge*. In these developments, rainfall is captured on the green roofs, returned to ground water through infiltration, and re-used for irrigation, toilet flushing, etc.

C. Examples of Extensive Green Roofs in North America

Thirty-five years of German experience and research indicates that extensive green roofs will succeed in most climates, if properly designed. With appropriate plant selection, sufficient drainage, and adequate structural support for the additional dead weight, green roofs will survive winter ice build-up. However, buildings in arid (desert) zones may not be good candidates for extensive green roofs, due to the difficulties and expense of water distribution and retention.

In North America, examples of extensive green roof projects are present in most climate zones, including New England, Mid-Atlantic, Gulf Coast, Midwest, Pacific Northwest, and Southern California regions. Ten or fifteen of these were built prior to 2002, and can be expected to have reached maturity by spring of 2003.

Because the few North American roofs that have been built to date demonstrate such a wide variety of settings and approaches, it is impossible to highlight "representative" case studies here. However, many updated case studies of green roof projects, including both extensive and intensive designs, are available at Greenroofs.com.

RELEVANT CODES AND STANDARDS

In the United States, green roof designs are generally regulated using existing standards for ballasted roofs. The International Code Council (ICC) code, formerly the BOCA code, used for guidance by many municipal authorities, recognizes roof gardens. It requires that the 'wet weight' of the green roof be treated as an additional dead load. It also supplies live load requirements for maintenance-related foot traffic and for regulated pedestrian access. One limitation of the ICC standards is that it does not specify the testing methods to be used in satisfying the code. ICC also provides standards for parapet heights and requirements for railings.

Trade organizations such as National Roofing Contractors Association (NRCA) are developing guidelines for waterproofing with green roof installations in mind. In addition, American Standard Testing Methods (ASTM), through the Green Roof Task Group E06.71, is in the process of developing guidelines and testing procedures specifically for green roof products.

However, at present, the only accepted guidelines for green roof construction are those developed by Forschungsgesellschaft Landschaftentwicklung Landschaftsbau. e.V. (FLL), *in Germany (Guidelines for Planning, Installation, and Maintenance of Green Roofs*, Richtlienien für die Plannung, Ausführung und Pflege von Dachbegrünungen, Forschungsgesellschaft Landschaftentwicklung Landschaftsbau. e.V.). These standards and guidelines are comprehensive, and include industry standard tests for medium weight, moisture, nutrient content, grain-size distribution, etc. The 1995 edition of the guide is available in English. The English translation can be purchased directly from FLL or through Roofscapes, Inc.. FLL also certifies laboratories to conduct critical tests such as the root penetration resistance of waterproofing membranes. Many green roof products available in the United States have FLL certification.

ADDITIONAL RESOURCES

WBDG

Optimize Site Potential, Minimize Energy Consumption, Protect and Conserve Water

General Information

Non-commercial organizations that can provide current lists of green roof service providers and are a useful source of up-to-date information, include:

National Agencies and Nonprofit Organizations	Headquarters
U.S. Environmental Protection Agency	Washington, DC
U.S. Green Building Council	Washington, DC
Green Roofs for Healthy Cities Coalition	Toronto, ON, Canada

In addition, some regional groups and agencies have distinguished themselves in the promotion of green roofs. These include the Earthpledge Foundation in New York City, Northwest Eco-Builders Guild, and Cleveland Green Building Coalition. In particular, the City of Portland, Oregon Ecoroof Program offers a guide to best management practices offers a useful "Vegetated Roof Cover Fact Sheet".

Design and Analysis Tools

The following table provides links to key analysis, simulation, and research evaluating and predicting the performance of green roofs.

Benefit	Activity	Organization	Contacts
Storm Water Management	Research	Michigan State University	Bradley Rowe Clayton Rugh
	Research	North Carolina State Univ., Water Resource Institute	Greg Jennings Bill Hunt
	Research	Pennsylvania State Univ., Center for Green Roof Research	David Beattie
	Research	Portland Bureau of Environmental Services	Tom Liptan
Water Quality	Research	University of Applied Sciences Neubrandenburg	Manfred Köhler Marco Schmidt
Thermal Properties	Analysis & Simulation	Shade Consulting, Inc.	Chris Wark
Thermal Properties	Research	Pennsylvania State Univ. Center for Green Roof Research	David Beattie
	Research	Canadian National Research Council, Inst. for Research and Construction	Karen Liu
Habitat Creation	Research	University of Applied Science Wädenswil	Stephan Brenneisen
	Research	Optigrüen International AG	Gunter Mann

German universities with significant on-going research in the science and engineering of green roofs include:

- Weihenstephan Fachhochschule
- Bayerische Landesanstalt für Weinbau und Gartenbau (LWG), Veithöchstheim
- Universität Hannover
- Techniche Universität Neubrandenburg
- Universität Essen

Publications

Building Technologies Associated with Rooftop Greening for Better Environment—The Building Centre of Japan also has a comprehensive and explanatory publication. Portions of the site and document are only available in English, but a translator may be required for the other parts in Japanese.

Dach + Grün—the most respected green roof publication worldwide, a German language quarterly published by FBB (Fachvereinigung Bauwerksbegrünung e.V.). To subscribe contact Verlag Dieter A. Kuberski GmbH, Postfach 102744, 70023 Stuttgart, Germany (Fax 011-711-2388619)

Green Roof Infrastructure Monitor—the most comprehensive English language periodical dedicated to green roofs is published quarterly by Green Roofs for Healthy Cities (GRHC). A quarterly web-based publication, *Green Roof Infrastructure Journal*, is available to GRHC members.

Commercial Resources

Two national companies in North America offer complete green roof building systems, independent of any particular waterproofing product:

- Roofscapes, Inc., and
- Tecta America Corp.

In addition, vegetated roof covers may now be purchased in conjunction with most conventional waterproofing systems, some of which have been tested by FLL for compatibility with green roofs. At least ten North American roofing companies offer green roof assemblies as standard auxiliary products, and more companies are entering the field all the time.

Home | LID Background | Design | Site Map

Low Impact Development Center, Inc.

Green Roofs

DISCLAIMER

BUILD IT!

AUTOCAD #1
AUTOCAD #2
AUTOCAD #3
AUTOCAD #4
AUTOCAD #5
JPEG #1
JPEG #2
JPEG #3
JPEG #4
JPEG #5
SPECIFICATIONS

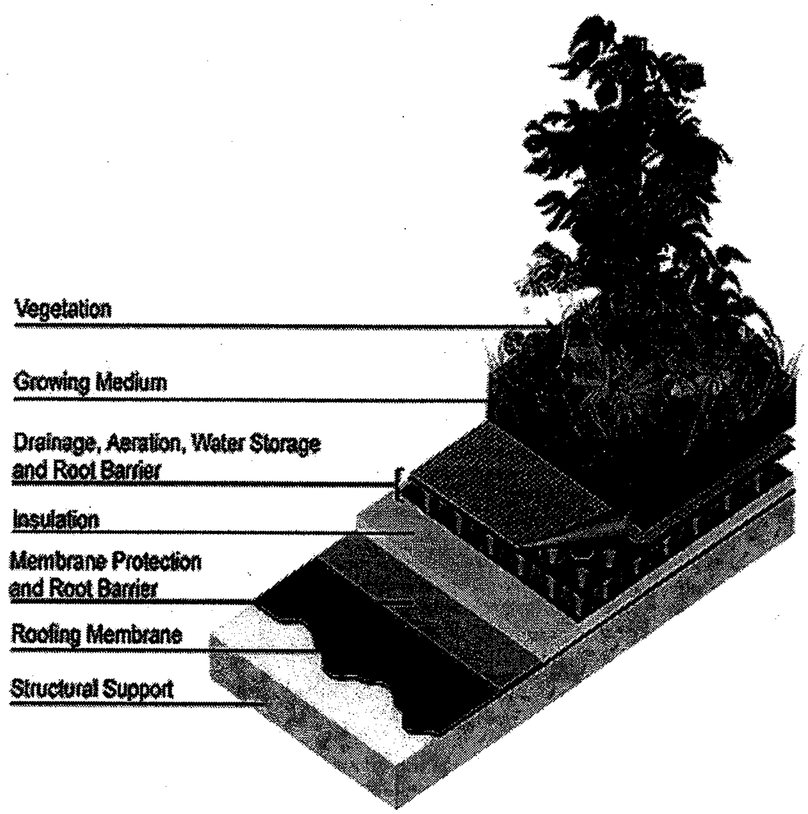
RELATED INFO

COSTS
MAINTENANCE

WHY?

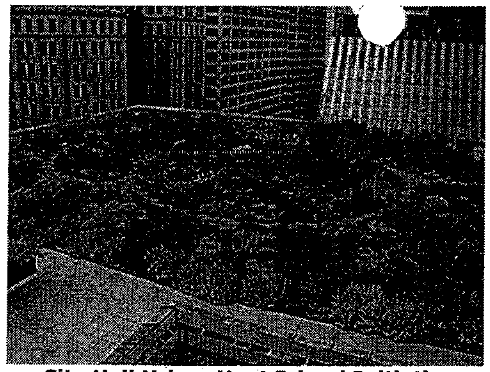
BENEFITS

Green roofs, also known as vegetated roof covers, eco-roofs or nature roofs, are multi-beneficial structural components that help to mitigate the effects of urbanization on water quality by filtering, absorbing or detaining rainfall. They are constructed of a lightweight soil media, underlain by a drainage layer, and a high quality impermeable membrane that protects the building structure. The soil is planted with a specialized mix of plants that can thrive in the harsh, dry, high temperature conditions of the roof and tolerate short periods of inundation from storm events.[1]



Green roof cross-section
(Source: American Wick Drain Corp.)

Historically, engineered green roofs originated in northern Europe, where sod roofs and walls have been utilized as construction materials for hundreds of years. The development of contemporary approaches to green roof technology began in the urban areas of Germany over 30 years ago. Because of ongoing water quality degradation and a limited existing infrastructure for the control of stormwater in these areas, few alternatives were available for improved stormwater management designs. Environmental and economic considerations helped spur the development of green roof systems that could provide the necessary stormwater treatment on-site. Roofscapes, Inc. have developed a numerical saturate-unsaturated flow simulation model that investigates the variables influencing the effectiveness of green roofs.[2]



Chicago City Hall Urban Heat Island Initiative project
(Source: Roofscapes, Inc.)

Green roofs provide stormwater management benefits by:

- Utilizing the biological, physical, and chemical processes found in the plant and soil complex to prevent airborne pollutants from entering the storm drain system.
- Reducing the runoff volume and peak discharge rate by holding back and slowing down the water that would otherwise flow quickly into the storm drain system.

Green roofs are not only aesthetically pleasing, but they also:

- Reduce city "heat island" effect
- Reduce CO_2 impact
- Reduce summer air conditioning cost
- Reduce winter heat demand
- Potentially lengthen roof life 2 to 3 times
- Treat nitrogen pollution in rain
- Negate acid rain effect
- Help reduce volume and peak rates of stormwater

The hydrologic processes that can be influenced by design choices and aid in the management of stormwater include:[3]

- Interception of rainfall by foliage, and subsequent evaporation.
- Reduction in the velocity of runoff.
- Infiltration.
- Percolation.
- Shallow subterranean flow, through the soil.
- Root zone moisture uptake and evapotranspiration.

[1] Exploring the Ecology of Organic Green Architecture, Green Roofs Web Site, (www.greenroo n), Velazquez

[2] Miller, C. and Pyke, G. 1999. *Methodology for the design of Vegetated Roof Covers.* Proceedings of the 1999 International Water Resource Enginee Conference, ASCE, Seattle, WA.

[3] Roofscapes, Inc., Green Technology For the Urban Environment., (www.roofmeadow.com), C. miller

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Vegetated Roof Cover

Philadelphia, Pennsylvania

Key Concepts:

- Structural Control
- Retrofit Opportunity
- Volume Reduction
- Life Cycle Costs

LOW-IMPACT DEVELOPMENT CENTER

Introduction

Vegetated roof covers on industrial and office buildings have been used in Europe for more than 25 years to control runoff volume, improve air and water quality, and promote energy conservation. These systems, known as "green roofs" or "extensive roof gardens," also have aesthetic benefits. They typically include layers of drainage material and planting media on a high-quality waterproof membrane. These systems use foliage and a lightweight soil mixture to absorb, filter, and detain rainfall. Some of the conditions responsible for the promotion and acceptance of green roofs in Europe, which many American cities face as well, are

- Widespread implementation of stormwater-related fees or taxes
- Laws requiring mitigation or compensation for the elimination of open space
- Densely populated areas with high real estate values
- Requirements to reduce loads on combined sewer systems (CSSs)

Project Area

The demonstration project was installed on the roof of the Fencing Academy of Philadelphia (Figure 1). Like many urban areas on the East Coast, Philadelphia experiences frequent, small, high-intensity storm events. These short-duration events frequently overload and surcharge sewer systems. In the Philadelphia region, storms with 24-hour volumes of 2 inches or less contribute 90 percent of all rainfall. Vegetated roof covers are designed to control these

Project Benefits:

- Runoff Reduction
- Air & Water Quality Improvement
- Aesthetics
- Energy Conservation

high-intensity storms by intercepting and retaining water until the rainfall peak has passed, while also allowing larger storm events to be safely conveyed away from the building.

Vegetated roofs are complex structures that require consideration of the load-bearing capacity of roof decks, the moisture and root penetration resistance of the roof membrane, hydraulics, and wind shear.

The plants help recreate the hydrologic function of open space in the following ways:

- Capturing and holding precipitation in the plant foliage
- Absorbing water in the root zone

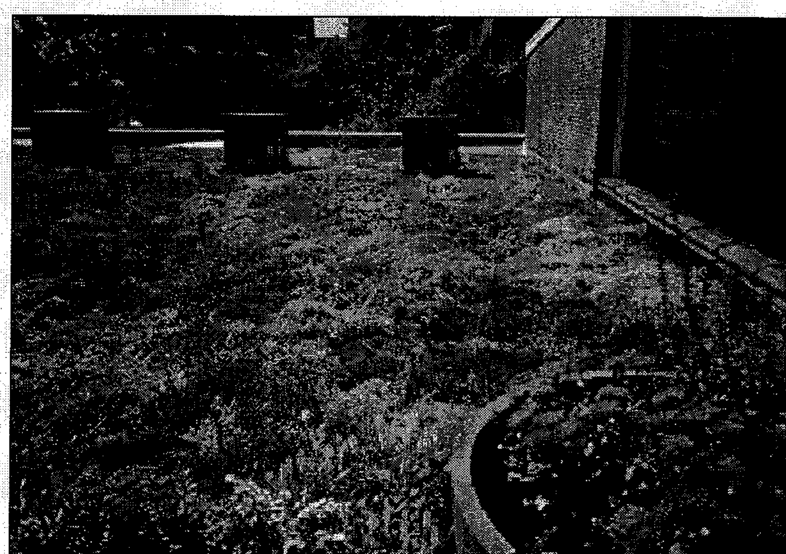

Figure 1. Fencing Academy of Philadelphia vegetated roof cover.

- Slowing the velocity of direct runoff by extending the flow path through the vegetation
- Cooling the temperature of the air and runoff. (Green roofs can be very effective measures for reducing the "thermal shock" caused by flash runoff from hot roof surfaces.)

Project Description

The vegetated rooftop project at the Fencing Academy of Philadelphia is a 3,000-square-foot vegetated cover installed and monitored by Roofscapes, Inc., on top of an existing structure (Figure 1). The roof system was intended to mimic the natural hydrologic processes of interception, storage, and detention to control the 2-year, 24-hour storm event. The distinguishing features of this system include

- Synthetic under-drain layer that promotes rapid drainage of water from the surface of the roof deck
- Thin, lightweight growth media that permits installation on existing conventional roofs without the need for structural reinforcement
- Meadow-like setting of perennial *Sedum* varieties that have been selected to withstand the range of seasonal conditions typical of the Mid-Atlantic region without the need for irrigation or regular maintenance

The installed vegetated roof cover is only 2.74 inches thick including the drainage layer. The system weighs less than 5 pounds per square foot when dry and less than 17 pounds per square foot when saturated. The saturated moisture content of the media is 45 percent by volume. The saturated infiltration capacity is 3.5 inches per hour. Figure 2 shows the components of the roof system.

The runoff characteristics of the roof were simulated using rainfall records for 1994 from eastern Pennsylvania. The model predicted a 54 percent reduction in annual runoff volume. The model also predicted attenuation of 54 percent of the 24-hour, 2-year Type II storm event and 38 percent of the 24-hour, 10-year Type II storm event. Additionally, monitoring at a pilot-sized project for real and synthetic storm events was conducted for a period of 9 months at 14- and 28-square-foot trays. The most intense storm monitored was a 0.4-inch, 20-minute thunderstorm. The storm event occurred after an extended period of rainfall had fully saturated the system. Figure 3 shows the runoff attenuation effectiveness for this event. Although 44 inches of rainfall was recorded during this period, only 15.5 inches of runoff was generated from the trays. Runoff was negligible for storm events with less than 0.6 inch of rainfall.

Project Summary and Benefits

This project showed that vegetated rooftop covers can help to reduce peak runoff rates for a wide range of storm events. The project also demonstrated that existing structures can be successfully retrofitted to help prevent CSS surcharging in urban areas. Significant energy

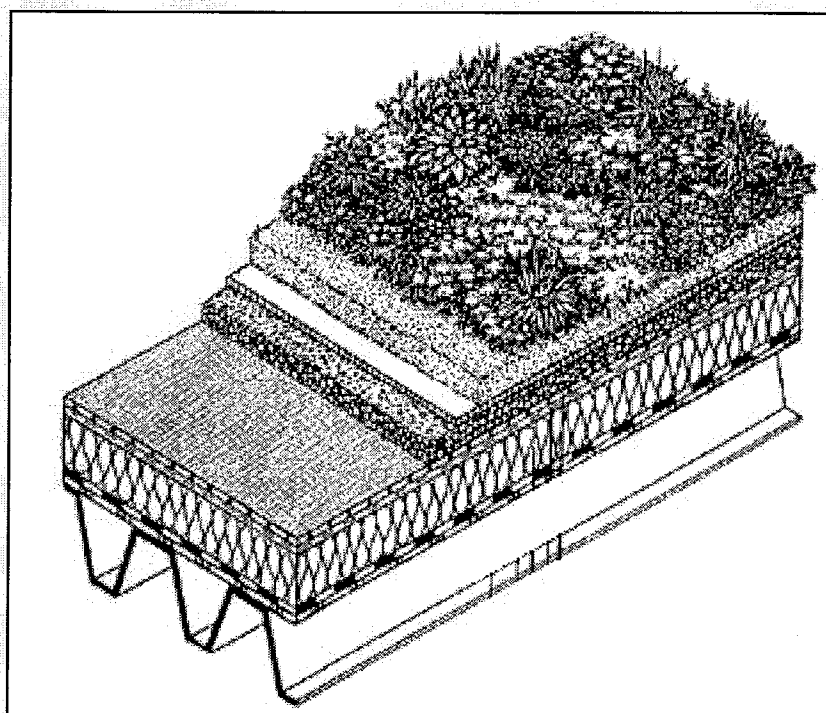

Figure 2. Components of the vegetated roof cover.

conservation benefits also are associated with vegetated rooftop covers. During the spring and summer, temperatures on a neighboring black tar roof varied by as much as 90 °F, while the variation under the 2.74-inch vegetated cover was only 18 °F. The vegetated cover also insulates the roof in winter, and the vegetation protects the roof membrane from the elements. Vegetated rooftop covers can potentially extend the life of a roof by 20 years or more.

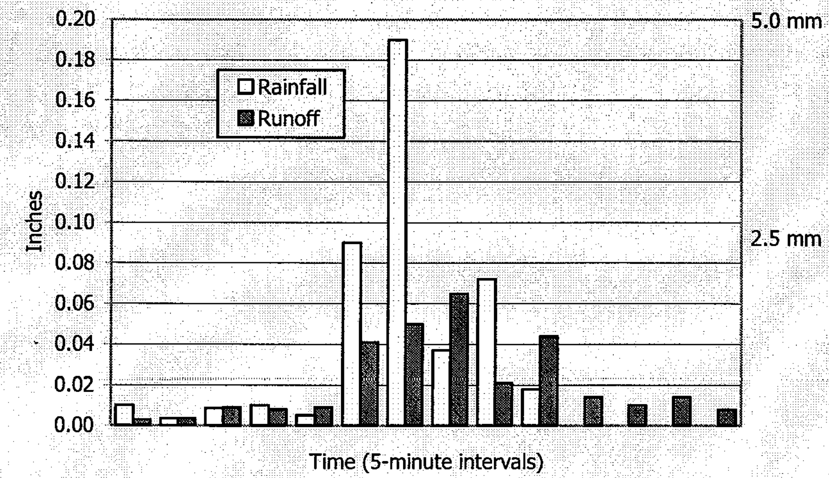

Figure 3. Runoff attenuation efficiency for a 0.4-inch rainfall event with saturated media.

References

Miller, C. 1998. *Vegetated Roof Covers: A New Method for Controlling Runoff in Urbanized Areas*. Pennsylvania Stormwater Management Symposium, October 21-22, 1998, Villanova University, Villanova, Pennsylvania.

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BMP T5.31 Vegetated Rooftops (Green Roofs)

Purpose and Definition

Vegetated rooftops, also know as green roofs or eco-roofs, are veneers of living vegetation that are installed on top of conventional roofs. A green roof is an extension of the existing roof, which involves a special root repelling membrane, a drainage system, a lightweight growing medium, and plants.

Applications and Limitations

Vegetated rooftops offer a practical method of managing runoff in densely developed urban neighborhoods and can be engineered to achieve specific stormwater runoff control objectives.

In North America, the benefits of green roof technologies are poorly understood and the market remains immature, despite the efforts of several industry leaders. In Europe however, these technologies have become very well established. Local building officials should be consulted early in the planning stage about building code requirements or prohibitions for vegetated rooftops.

Design Guidelines

Vegetated rooftops achieve runoff control by mimicking a variety of hydrologic processes that are associated with open space. These include:

- Interception of rainfall by foliage
- Direct runoff
- Infiltration
- Percolation
- Shallow subterranean flow (i.e., analogous to shallow ground water flow)
- Root zone moisture uptake and subsequent evapotranspiration

In a vegetated roof cover, all of these functions occur in a thin layer, typically 10 to 20 cm in depth. Through careful design, these hydrologic processes can be modulated to achieve specific outcomes. Vegetated roof covers can be considered as falling into three categories. These are:

1. Single layer system with free drainage.
2. Multi-layer system with a freely-drained basal drainage layer.
3. Multi-layer system, incorporating restricted drainage that causes a free water surface to form inside the drainage layer (integral storage).

It is important to properly specify the hydraulic properties of materials used in constructing vegetated roof covers. Both the growth media and the drainage layer play an important role in controlling runoff. Growth media properties, including saturated hydraulic conductivity, porosity, and moisture retention exert influence when the cover is dry. When the cover has been soaked by antecedent rainfall, the transmissivity of the drainage layer is more important.

It is important to consider practical limitations as well as hydraulic considerations. Hydraulic conductivity of growth media should not be less than 0.03 cm/min to prevent anaerobic conditions from becoming established. Designs that incorporate less transmissive drainage layers will be associated with the transient build-up of hydrostatic pressure over some areas of the waterproofing membrane. This may not be desirable, especially in retrofit situations.

Allowable load capacities of roofs may also constrain the depth of cover.

Resource Material

Miller, C. and Grantley Pyke. Methodology for the Design of Vegetated Roof Covers, Proceedings of the 1999 International Water Resources Engineering Conference, Seattle, Washington.

Rainwater Harvesting

Rainwater harvesting consists of collecting runoff from a catchment area and storing it for on-site use, instead of releasing the water. Using harvested rainwater can mitigate some of the increased runoff volume associated with the construction of impervious rooftops, and also reduces the demand on potable water supply systems.

Rainwater is filtered before being stored in a cistern. When rainwater is used indoors or subject to human contact, sterilization is highly recommended and may be required by plumbing codes. There are many possible ways to implement rainwater harvesting systems that include filtering and often pumps.

A possible limitation to the use of rainwater harvesting systems is water rights permitting with the Washington State Department of Ecology. While the State has informally indicated that "small" systems would not be required to obtain water rights, an attempt in spring 2005 to pass legislation formally authorizing construction of systems 5,000 gallons and smaller was unsuccessful.

International Rainwater Catchment Systems Association
http://www.ircsa.org/index.htm

State of Texas
http://www.twdb.state.tx.us/assistance/conservation/Alternative_Technologies/Rainwater_Harvesting/Rain.asp

Rain Barrel Information and Sources
http://dnr.metrokc.gov/wlr/PI/rainbarrels.htm

Special Circular 277

Rainwater Cisterns

Design, construction, and water treatment

PENNSTATE

1855

College of Agricultural Sciences • Cooperative Extension

Contents

Prepared by Edward S. Young, Jr., and William E. Sharpe, former research assistant in the Environmental Resources Research Institute and associate professor of forest hydrology, School of Forest Resources and Environmental Resources Research Institute, respectively.

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Penn State College of Agricultural Sciences research, extension, and resident education programs are funded in part by Pennsylvania counties, the Commonwealth of Pennsylvania, and the U.S. Department of Agriculture.

This publication is available from the Publications Distribution Center, The Pennsylvania State University, 112 Agricultural Administration Building, University Park, PA 16802. For information telephone (814) 865-6713.

Issued in furtherance of Cooperative Extension Work, Acts of Congress May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture and the Pennsylvania Legislature. T. R. Alter, Director of Cooperative Extension, The Pennsylvania State University.

Roof-catchment cisterns are systems used to collect and store rainwater for household and other uses. Such systems basically consist of a house roof, or catchment, and a storage tank, or cistern. A system of gutters and downspouts directs the rainwater collected by the roof to the storage cistern. The cistern, typically located underground, may be constructed of various materials including cinderblock, reinforced concrete, or precast concrete, fiberglass, or steel. The cistern supplies water to the household through a standard pressurized plumbing system. A typical arrangement for a roof-catchment cistern system is shown in Figure 1.

The use of rainwater cisterns is by no means new. They were utilized by both Greek and Roman civilizations, as well as by Pacific island inhabitants prior to any contact with western civilization. Nevertheless, the same basic principles of modern-day systems were used in the roof-catchment cisterns of these earlier times.

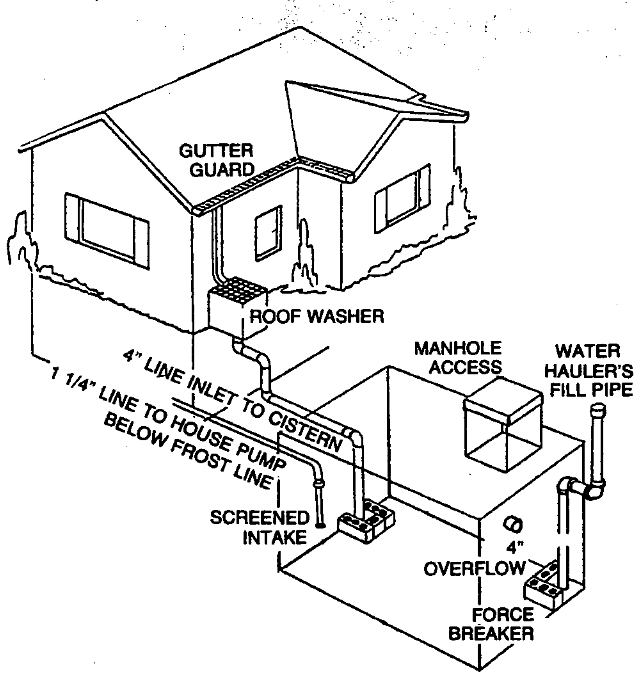


Figure 1. Typical roof-catchment cistern system. (Source: Water Filtration Co. customer information brochure. Water Filtration Co., 108B Industry Rd., Marietta, Ohio 45750.)

Current use of rainwater cisterns may be increasing. Those who live in areas where groundwater and surface water are unobtainable or unsuitable for use have been compelled to resort to other sources of water. Rainwater collection on a household scale is quite practical in areas where there is adequate rainfall, and other acceptable sources of water are lacking. The coal strip-mining region of western Pennsylvania is one such area. Mining has rendered much of the ground and surface water unfit for drinking or other uses in large portions of these areas. Rural residents have been forced to find other sources of water and they have invariably turned to roof-catchment cisterns.

Roof-catchment cisterns may also be used to supply water to farms. Watering troughs and rain barrels can be filled by water collected from barn and other out-building roofs. A storage cistern built alongside a barn or other building could serve as an emergency source of water for firefighting in the event that a pond were not nearby. However, the use of rainwater for supplying domestic water needs is not without its problems.

Water *quality* is of concern especially when the rainwater is to be used for drinking purposes in addition to other domestic uses. Rainwater and atmospheric dust that are collected by roof catchments contain certain contaminants which may pose a health threat to those consuming the water. Lead and other pollutants may accumulate in cistern bottom sediments; and untreated rainwater is quite corrosive to plumbing systems. Measures must be taken to minimize these and other water-quality problems in cistern systems. Recommendations for doing this will be presented, as well as guidelines for designing and building roof-catchment cistern systems.

Rainwater cisterns can provide water of adequate quantity *and* quality if proper steps are taken in the planning and construction stages, and periodic maintenance is performed throughout the life of the cistern.

Cistern design

The storage capacity of a rainwater cistern depends on several factors:

- the amount of rainfall available for use,
- the roof-catchment area available for collecting that rainfall,
- the daily water requirements of the household,
- and economics.

All but the first of these factors can be controlled to some extent by the cistern owner.

Available rainfall

Across most of Pennsylvania, annual rainfall averages around 40 inches (Figure 2). During drought years there may be as little as 30 inches, while excessively wet years may produce 50 or more inches of rainfall. For most planning purposes, the average figure should be used. However, designing a cistern based on the lowest figure would guarantee enough storage to get you through even the driest years.

Due to evaporative, snow and ice, and roof-washer losses (to be discussed later), only about two-thirds of the annual total rainfall is actually available for cistern storage.

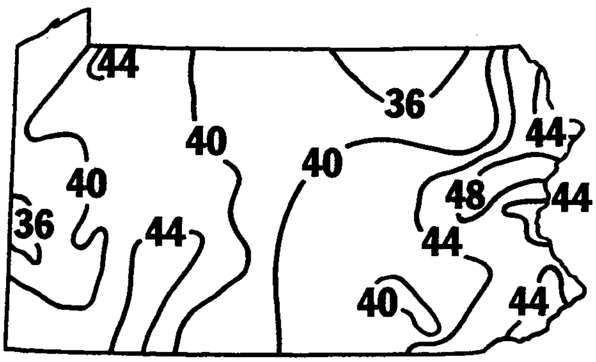


Figure 2. Average annual precipitation for Pennsylvania (inches)

Daily water needs

The amount of water you design your roof-catchment cistern to collect and store depends upon your daily water needs. If you have a small catchment area and low-volume cistern then your water use will be limited accordingly. So it is important when designing a roof-catchment cistern system to have some idea how much water you will require from it every day.

Various estimates of household water use have been published. The average base use determined by water utilities is 7500 gallons per month, which is equivalent to an average yearly minimum need of 90,000 gallons per household. Common household planning provides for 50 to 75 gallons a day per person, or 73,000 to 110,000 gallons a year for a family of four. One-third to one-half of this amount is used for flushing toilets. However, those who must rely solely on rainwater-fed supplies will undoubtedly use less water.

Studies of water use in the U.S. Virgin Islands and Hawaii, where rainwater cisterns are used extensively, indicate that this is generally the case. Water use from rainwater cisterns in the U.S. Virgin Islands averaged only 24 gallons a day per person for owner-residents. However, in Hawaii, where rainfall is much more plentiful (up to 160 inches annually) cisterns tended to be much larger and water use was considerably greater — over 100 gallons a day per person in many cases. Nevertheless, in both situations steps to conserve water were voluntarily implemented when cistern levels fell to low levels. As one cistern owner in the Virgin Islands commented, "We can make the last quarter of our cistern supply last about as long as the first three quarters."

It should be clear from this brief discussion of water use that there is considerable variation, depending on the circumstances. For purposes of general cistern design, the figure of 50 gallons a day per person is probably the best one to use. This figure would be applicable to a family living in a home with hot and cold running water and all the modern conveniences (including automatic washer and dishwasher), and no special water conservation measures. The installation of water-saving devices could considerably reduce household water use with no conscious effort on the part of family members. Additional information on water conservation in the home is available from your county extension office or directly from the Environmental Resources Research Institute, The Pennsylvania State University, University Park, Pennsylvania 16802. Ask for the pamphlet *Saving Money with Home Water Conservation Devices.*

Catchment area

The roof area to be used as the collection surface is usually predetermined by the size of the existing house or other outbuilding roofs. However, when planning a rainwater collection system from the ground up, where the size of the catchment is to be designed to suit domestic water needs, the following guidelines will be useful.

Figure 3 allows the catchment area required to be determined based on annual water needs and annual precipitation. As an example, suppose the average annual precipi-

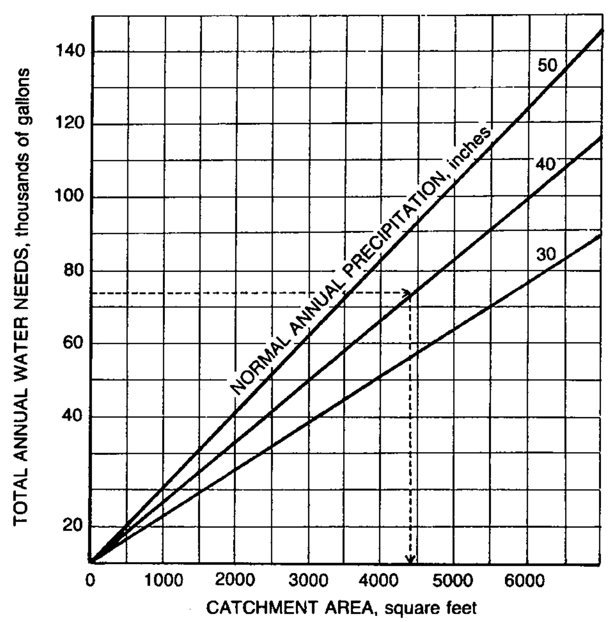


Figure 3. Graph used to determine catchment area needed. (Source: Midwest Plan Service, Iowa State Univ. 1968. Private Water Systems. p. 13.)

tation for your area is 40 inches. You have determined that your family of four requires 200 gallons a day or 73,000 gallons annually. From Figure 3 the needed catchment area is determined to be 4400 square feet. Note: Roof area can be determined by measuring the outside of the building or buildings to be used to collect rainfall. Do *not* measure the actual roof surface unless it is horizontal.

Cistern size

A cistern should have sufficient storage capacity to carry the household through extended periods of low rainfall. A three-month supply of water, or one-fourth of the annual yield of the catchment area, is generally adequate in areas such as Pennsylvania where the rainfall is distributed fairly evenly over the course of the year.

Figure 4 illustrates this idea. For example, if you have determined your annual domestic water needs to be 40,000 gallons (*and,* most importantly, you have enough catchment area and annual precipitation to supply this amount of water), then you should design and build a cistern with a 10,000-gallon storage capacity.

A *minimum* storage capacity of 5000 gallons is recommended for domestic cisterns. This capacity should eliminate having to buy or haul water, a practice that is not only inconvenient but can become somewhat costly. Remember these words of wisdom when designing your roof-catchment cistern: "You pay for a large cistern once and a small one forever . . . "

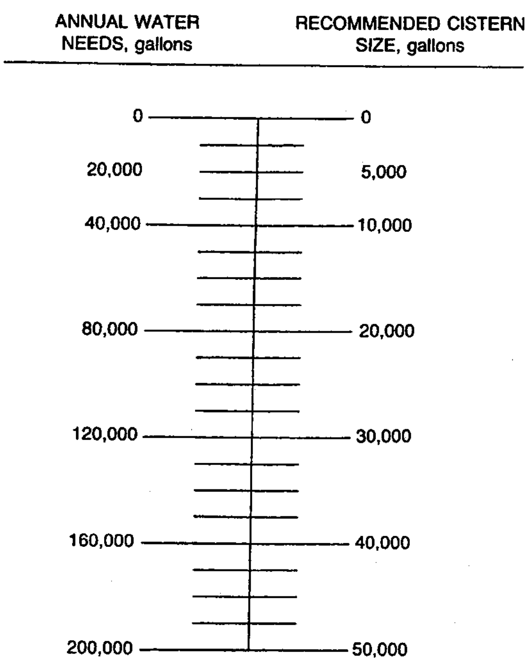


Figure 4. Cistern size based on a storage capacity equal to 1/4 of the annual water needs or a three-month supply of stored water.
(Source: Midwest Plan Service, Iowa State Univ., 1968. Private Water Systems. p. 15.)

Cistern construction

Location

Cisterns should be located as close as possible to the house or wherever the water is to be used. They may be built above or below ground, but below-ground cisterns are recommended in this part of the country to avoid freezing during the winter months. Underground cisterns also have the advantage of providing relatively cool water even during the warmest months of the year. Cisterns may be incorporated into building structures, such as in basements or under porches. This way you can use foundation walls for structural support as well as for containment of stored rainwater.

A cistern should be located where the surrounding area can be graded to provide good drainage of surface water *away* from the cistern. Avoid placing cisterns in low areas subject to flooding. Both of the above steps will reduce the chance of storm runoff contaminating the stored cistern water.

Cisterns should always be located upslope from any sewage disposal facilities; at least 10 feet away from watertight sewer lines and drains, at least 50 feet away from non-watertight sewer lines and drains, septic tanks, sewage absorption fields, vault privies and animal stables, and at least 100 feet away from sewage cesspools and leaching privies.

It pays to check these things out carefully *before* turning the first shovelfull of earth for the cistern excavation. A contaminated cistern is not worth very much.

In certain situations, such as a barn or other outbuilding roof that supplies collected rainwater to a house downslope, cisterns may be located so as to provide gravity flow to the place of use. This setup is definitely preferable if it can be worked into your particular system. However, in most cases the level of water stored in underground cisterns is lower than the points of use within the distribution system so a pump and pressurized system are usually required.

Construction

Cisterns can be constructed from a variety of materials including cast-in-place reinforced concrete, cinderblock and concrete, brick or stone set with mortar and plastered with cement on the inside, ready-made steel tanks, precast concrete tanks, redwood tanks, and fiberglass. Cast-in-place reinforced concrete is considered best, especially for underground cisterns. However, cinderblock-walled cisterns with concrete floors are common and are quite satisfactory for below-ground construction; these will usually be somewhat less expensive than the all-concrete version. Concrete walls and floors should be at least 6 inches thick and reinforced with steel rods.

Two plans for below-ground concrete cisterns are shown in Figures 5 and 6. Figure 5 shows a concrete block-walled version and Figure 6 shows an all-concrete version with a sand and gravel filter on top of the cistern.

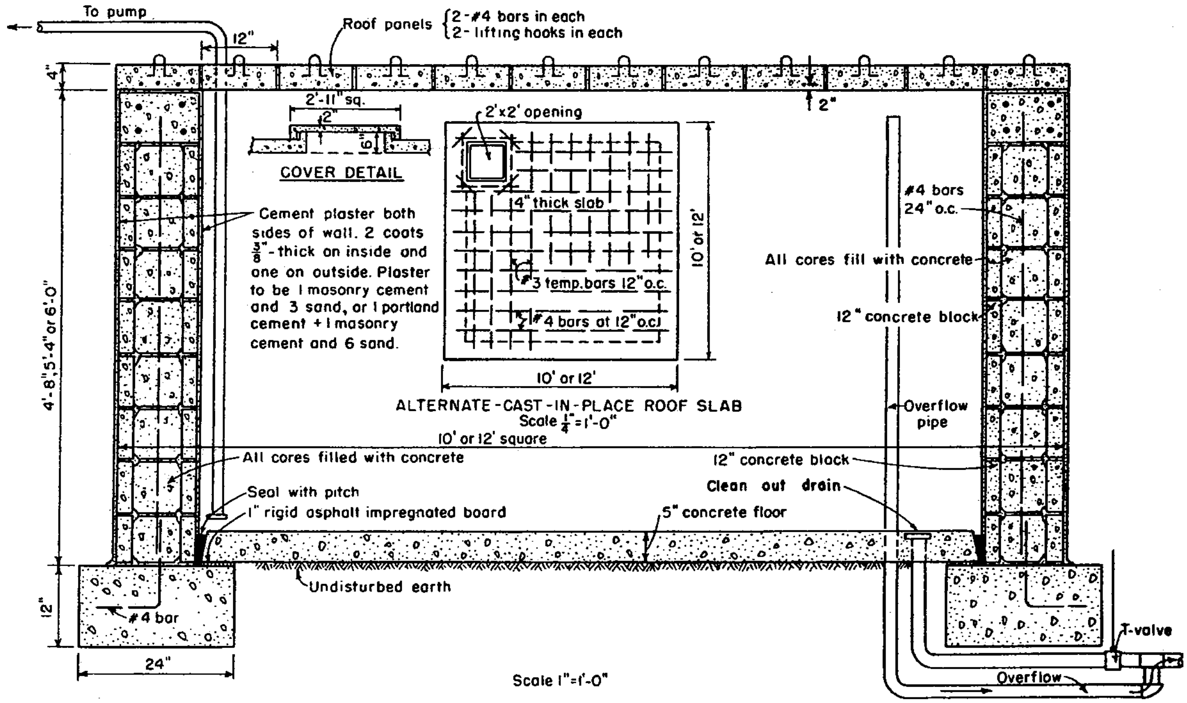


Figure 5. Cross section of a concrete block-walled below- ground cistern, showing important features.
(Source: PSU Ag. Ext. Service, Order #800-86 Concrete Masonry Cisterns)

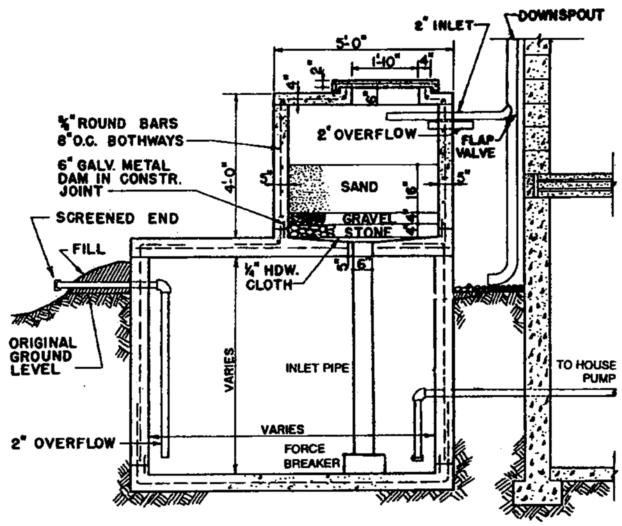


Figure 6. Cross section of concrete cistern with filter
(Source: PSU Ag Ext. Service, Order #800-87 Concrete Cisterns)

If cinderblock or concrete block is used for the walls of the cistern, all hollow cores should be filled with concrete and reinforcing rods should be placed vertically to add strength to the structure. Footers may be necessary for larger cisterns, as shown in Figure 5.

The top of the cistern should be of reinforced concrete and should fit tightly onto the rest of the structure. The top may consist of individual panels as shown in Figure 5, or it may be a one-piece slab, like that shown in Figure 6. In any event, a manhole through the top of the cistern to allow access to the storage tank should be included. Such an opening should be at least 2 feet across. A heavy concrete or iron lid like that shown in Figures 5 and 7 should be fitted tightly over the opening to prevent the entrance of light, dust, surface water, insects and animals.

Manhole openings should have a watertight curb with edges projecting several inches above the level of the surrounding surface. The edges of the manhole cover should overlap the curb and project downward a minimum of 2 inches. Manhole covers should be provided with locks to further reduce the danger of contamination and accidents.

Place the manhole opening near a corner or an edge of the structure so that a ladder can be lowered into the cistern and braced securely against a wall. This access is necessary for the periodic maintenance tasks, to be discussed

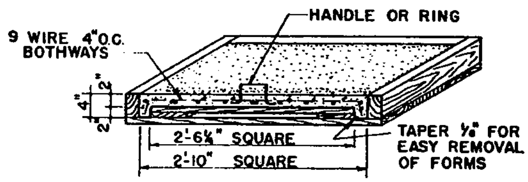


Figure 7. Section thru form for manhole cover.

later. An alternative is to build concrete steps and handholds into the cistern wall beneath the opening.

The interior walls and floor of the cistern should be smooth to make cleaning easier. A cement plaster can be spread over the interior, depending on how rough the basic construction is. Cement-base sealants, such as Thoroseal and Sure-Wall, can be applied to the interior as well, to provide a smoother finish and further protection against leakage. A cistern that leaks is not only useless but it is dangerous as well; if stored water can leak out, contaminated surface or ground water can leak in. It is worth the time when building a cistern to do it *right* — get a good builder who will guarantee his work against leakage.

Vinyl liners may be used to prevent leakage in some cisterns, but they are usually troublesome. They are expensive, prone to puncture, and they prevent the use of cleanout drains and other accessories inside the cistern. Try a vinyl liner only as a last resort when all other efforts to prevent leakage have failed.

Another important feature of a well-designed cistern is an overflow pipe or pipes. Two different possibilities are shown in Figures 5 and 6. In Figure 5 the overflow is in the form of a standpipe that leads through the floor of the cistern to a drain. Such an overflow pipe, or any other cistern outlet for that matter, should *never* be connected to a sewer line, either directly or indirectly. The drain line shown in Figure 5 should lead to a free outlet downslope from the cistern. The diameter of the overflow pipe should be at least as large as the diameter of the inflow pipe from the roof catchment. Figure 6 shows an overflow pipe leading through a wall of the cistern directly to the outside.

The outside end of an overflow pipe should be *effectively* screened to prevent the entrance of animals and insects. A fine-mesh rust-proof screening should be used. The screening can be cut to a size large enough to be wrapped over the end of the overflow pipe and should be secured with a hose clamp or similar fastening device. A simple overflow design is pictured in Figure 8.

Large-diameter plastic pipe should be used for the overflow pipe in any case. Good drainage away from the cistern and house should be provided, when designing overflow outlets like those shown in Figures 6 and 8.

A cleanout drain is also shown in Figure 5. This is a very important feature that allows the cistern to be drained for periodic cleaning and maintenance. A cistern without a drain would have to be pumped out before any maintenance or cleaning could be done.

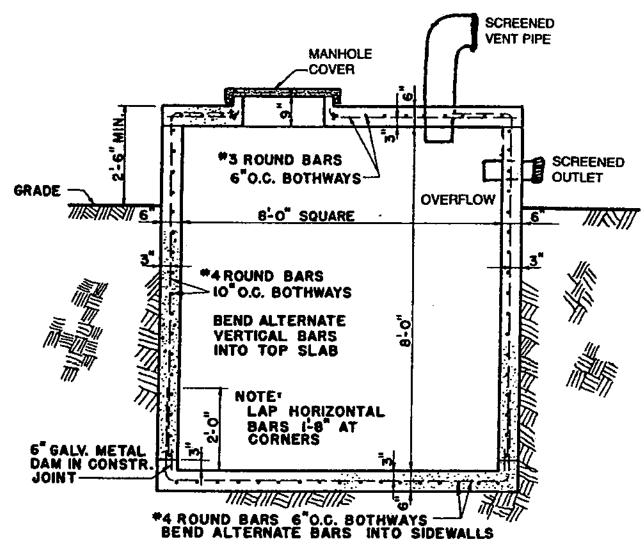


Figure 8. Cross section of 8' x 8' cistern showing overflow pipe, manhole, and vent pipe.

A cleanout drain should lead to a free outlet and never a sewer line. The floor of the cistern should be sloped slightly toward the drain to facilitate cleaning. A valve to open and close the drain could be controlled from above ground level as shown in Figure 9, or an underground pit could be built around the valve to provide direct access. See Figure 10. In either case, the valve and drain line should be insulated by a sufficient depth of earth to prevent freezing during even the most severe winter weather.

A cleanout drain line should be at least 3 or 4 inches in diameter to avoid clogging — a large amount of sediment may have to move through the line during cleaning operations. The outlet should be located where draining water will not cause any problems or complaints from neighbors.

Cisterns should be *vented* to allow fresh air to circulate into the storage compartment. One or more large-diameter pipes through the top of the cistern will serve this purpose, as shown in Figure 8. The outside opening of each pipe should be screened in the same manner as that described above for overflow pipes. The openings, located several feet above ground level, should face the direction of the prevailing winds, west in most cases, to maximize ventilation. Four- or six-inch diameter plastic pipe is good for vents. Make sure there is a watertight seal where each vent pipe goes through the top of the cistern.

The water line from the cistern to the house or other place of use should be buried below the frost line and should be 1 or 1 1/4 inches in diameter. The intake head should be effectively screened and elevated a minimum of one foot above the floor of the cistern to prevent sediment from being drawn into the distribution system. The portion

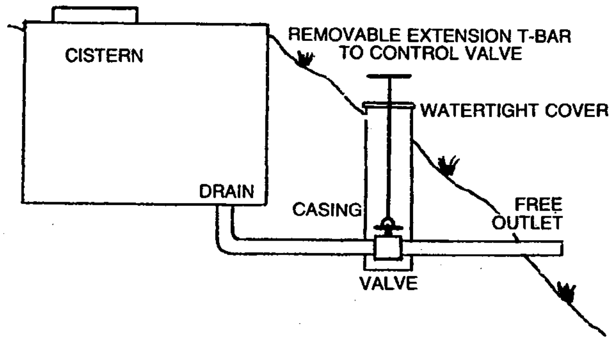


Figure 9. Plan for cleanout drain and control valve.

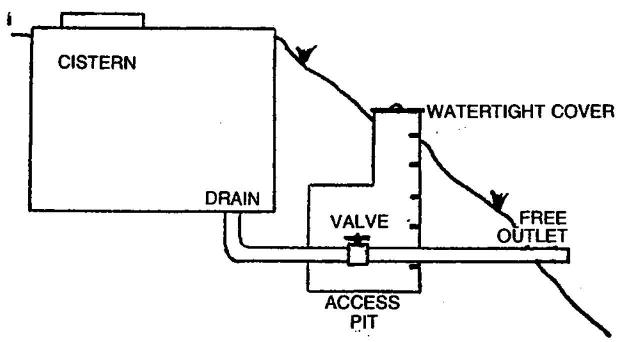


Figure 10. Plan for cleanout drain and control valve.

of the intake pipe within the cistern should be plastic. The best position for the intake is on the opposite side of the cistern from the roof-water input pipe.

A separate input pipe for adding hauled water is another important feature of the well-designed cistern. The system pictured in Figure 1 shows such a pipe. Where possible, it is best to locate the above-ground portion of the fill pipe near the driveway or other road surface, so that the water truck will not have to drive over your lawn to reach it. Four-inch plastic pipe makes a good fill pipe. A tight-fitting cap should be placed over the above-ground end of the pipe. You may want to padlock the cap to further reduce the possibility of contamination.

Water entering a cistern with any kind of force behind it, as during a summer thundershower, or from a water truck, tends to agitate the stored water and possibly stir up sediment unless steps are taken to lower the force of the incoming water. One way of doing this is through the use of "force breakers," as pictured in Figure 11.

Water entering the cistern from either the roof or a water truck should travel down a 4-inch plastic pipe into a force breaker box made from concrete blocks. The blocks should be set in mortar on the floor of the cistern with the cavities facing up. Slots or openings with an area of at least 13 square inches need to be cut into the lower end of the pipe to allow the incoming water to move from the pipe to the cistern. Force breakers should be installed under both roof-water and water-hauler inlets.

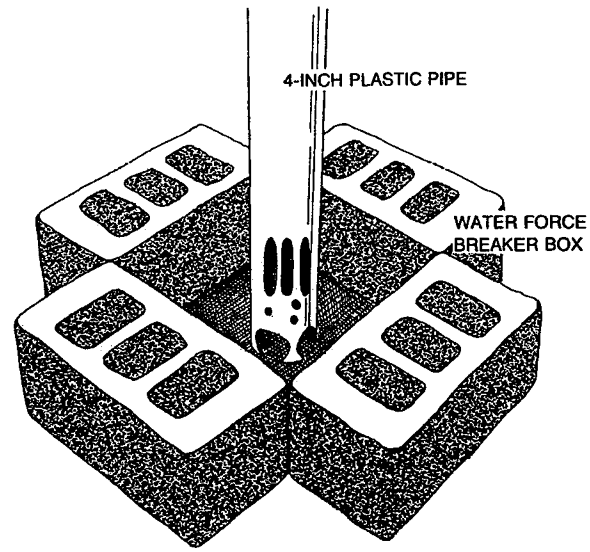


Figure 11. Water force breaker. Should be placed at all inlets to the cistern.
(Source: Water Filtration Co. customer information brochure. Water Filtration Co., 108B Industry Rd., Marietta, Ohio 45750.)

Roof washers

There are several other very important construction features that will help insure good quality cistern water. Roof washers and roof-water filters were mentioned earlier, and their importance and construction details will be discussed here.

A lot of dirt and dust collects on the roof-catchment surface between rainstorms. This debris can include particles of lead and other atmospheric pollutants as well as bird droppings. These contaminants will enter the cistern along with the roof water unless steps are taken to prevent contamination. The use of roof washers and roof-water filters can reduce the amount of these contaminants entering the system.

The first water to come off the roof at the beginning of a rainstorm is the most contaminated. The degree of contamination will depend on several things including the length of time since the last rainfall, proximity of the catchment to a highway or other local source of airborne pollution, and the local bird population. Also, certain types of materials are preferable for the catchment surface, as will be detailed later.

A roof washer is a mechanism that diverts this initial, highly contaminated roof water away from the cistern. Once the catchment surface has been washed off by an adequate amount of rainfall, the roof water is once again routed to the cistern for storage. Usually the first 0.01 inch of rainfall is considered to be adequate to remove most of the dust and dirt from the surface of the catchment. In this way, only the cleanest roof water is collected in the cistern, whereas the contaminated roof wash is discharged to waste.

There are several ways of accomplishing this. The roof water can be diverted manually through a series of valves within the spouting system, or automatic roof washers may be fabricated by the cistern owner or purchased from commercial distributors.

A simple roof-wash diverter is shown in Figure 12. This particular design requires manual operation of a flap valve to control the flow path of the roof water within the spouting system. Such a valve would be necessary on each downspout unless they all converged into a single pipe just before emptying into the cistern. This single-valve arrangement is definitely preferred since the operation of this type of diverter requires someone to go out and close the valve shortly after the rain begins, allowing the roof water to flow into the cistern. The valve should be located so that it can be reached or controlled from a covered porch or other roofed area adjacent to the house or cistern.

During periods when rains are separated by only brief periods of time (less than a day), it would not be necessary to divert the initial roof wash every time it began to rain. However, it is important to divert the initial roof water produced by the first rainfall following an extended dry period.

As far as determining how much roof water to allow to run to waste before routing it to the cistern, this will vary for each storm. You can use the visual appearance of the roof water as an indicator — if it runs *clear* to your eye when collected in a clear glass jar, *then* you can direct the water to the cistern for storage and subsequent use. Or, you can place a large 10- to 20-gallon container under the downspout draining to waste. The container should be sized to suit your particular roof area — 10 gallons per 1000 square feet of roof area. So, at the beginning of a rainstorm the dirty roof water is directed into the container; when it is full, you know that the catchment has been sufficiently rinsed and the roof water can thereafter be routed to the cistern. For this type of arrangement, a single roof-water collection vessel for the entire catchment would be best. Adequate drainage, such as into a gravel-filled hole, should be provided for the roof water that is to be wasted, whether or not it passes through a collection vessel first.

Figure 13 is an illustration of an automatic roof-wash diverter that does not require someone's presence to operate at the start of a rainstorm, as was the case for the previous design. The basic principle is the same. A certain quantity of contaminated roof water at the beginning of a rainstorm is collected in a vessel so that it cannot enter the cistern. Once the catchment has been rinsed off by a sufficient quantity of water, the roof water is again routed to the cistern. For the design pictured in Figure 13, the volume of the collection vessel should be 10 gallons per 1000 square feet of roof area. If more than one collection vessel is necessary, as in the case of a very large catchment, then the size of the vessels should be adjusted accordingly to provide for the entire catchment area.

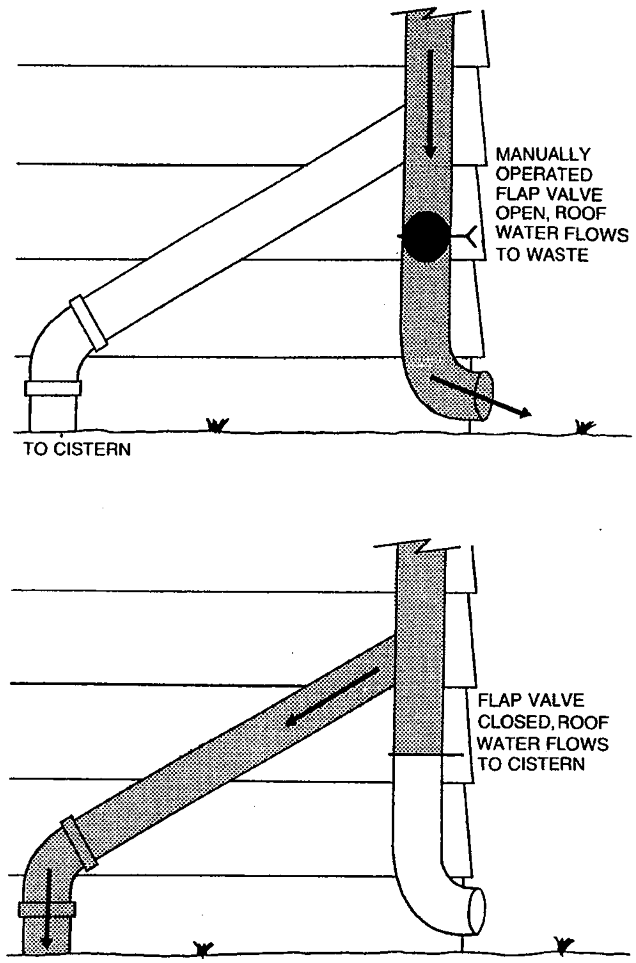
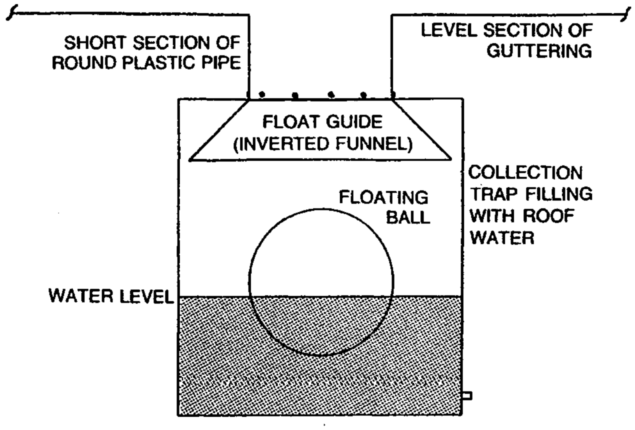


Figure 12. A simple roof-wash diverter.

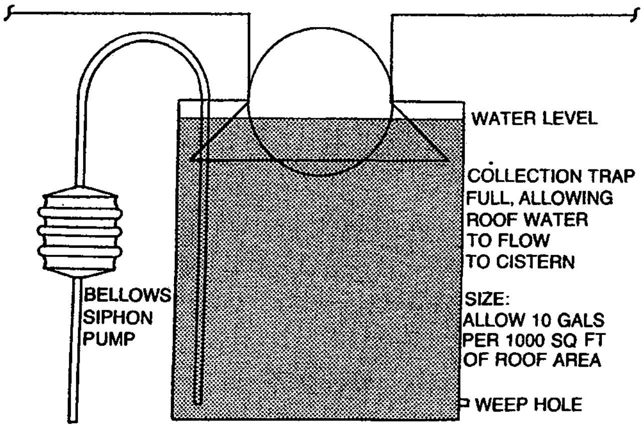
The design shown in Figure 13 is a fairly generalized one, in that few specifics are given for the components of the homemade roof washer. The collection vessel could be a large plastic or glass bottle, or a rain barrel or other similar container. Regardless of the type of container that is used, several important features should be included in such an automatic roof washer. These include a float to seal off the vessel or collection trap when full, tapered guides to insure that the float will not become lodged off to one side of the opening as the vessel fills, and provision for draining the collection vessel between storms.

A buoyant plastic ball several inches in diameter will



A

(Adapted from Jenkins, D. and F. Pearson. 1978. Feasibility of Rainwater Collection Systems in California. Calif. Water Resources Center, Univ. of Calif., Contrib. No. 173, p. 51.)



B

Figure 13. Automatic roof-wash diverter.

serve as the float in an automatic roof-wash diverter fashioned after that shown in Figure 13. Of course the ball must be slightly larger in diameter than the section of pipe leading into the top of the collection trap. This will keep the dirty roof water collected in the trap from escaping and flowing to the cistern once the trap is full. A soft rubber strip may be fastened around the lip of the pipe at the top of the collection trap where the ball will come to rest, to improve the seal.

As the collection trap fills and the float rises to the top, the float should be guided to the input pipe opening by means of an inverted funnel or similar device. Otherwise, the float may become lodged off to the side and thus will not block off the inflow pipe. The funnel or float guide should extend far enough toward the sides of the collection trap so that the float cannot possibly be caught up between the edge of the guide and the side of the collection trap. The float guide can be flared and attached to the input pipe by means of rustproof bolts, as pictured in Figure 13A. A plastic float guide is preferable; however, other materials such as galvanized steel, sheet aluminum, or tin are also acceptable for use in this portion of the roof-catchment system.

Some provision must be made for draining the automatic roof-wash diverter between rainstorms. This can be accomplished in a number of ways. Two are shown in Figure 13B. Either a simple bellows siphon pump or a small-diameter weep hole can be used to drain the water out of the collection trap. Although both of these mechanisms are shown in Figure 13B, only one of the two would be required in an actual system. If a siphon-pump were used, someone would be required to operate it following each rainstorm. The end of the siphon tubing inside the collection trap should be positioned at least 1/4 to 1/2 inch above the bottom of the collection trap, to avoid the layer of sediment that will accumulate there. If you decide to use a weep hole to drain your roof-water collection trap, it should be drilled through the side of the collection trap about 1/2 inch above the bottom and 1/16 inch in diameter. This will allow the water to slowly drain out of the collection trap during non-rain periods, yet the water will drain out slowly enough that very little will be lost during a rainstorm. A third method of draining the collection trap would simply be to install a faucet with valve on the side or bottom of the collection trap. The valve would be closed during rainfall events and opened during non-rain periods. This arrangement would also require someone to be there to operate the valve, although it could be done at one's leisure during non-rain periods.

Regardless of the type of waste outlet used on the collection trap, it should lead into a gravel-filled hole or to air, never into a sewer line. Also, a layer of sediment will accumulate on the bottom of any roof-water collection trap, necessitating periodic cleaning. These factors should be considered when planning the location and fitting of these units in your particular system.

If you do not want to construct your own roof-wash diverter, commercial units are available. The one pictured in Figure 14 is made of fiberglass and marketed by Water Filtration Co., 108B Industry Rd., Marietta, Ohio 45750, phone (614) 373-6953. This company also distributes information and other accessories for cistern operation.

Roof-water filters

In addition to roof washers, your roof-catchment system should also include a roof-water filter located between the catchment and cistern. Such a filter will primarily serve to remove gross particulates and associated contaminants from the water before it enters the cistern. It can also serve to neutralize the acidic rainwater to some extent if lime-

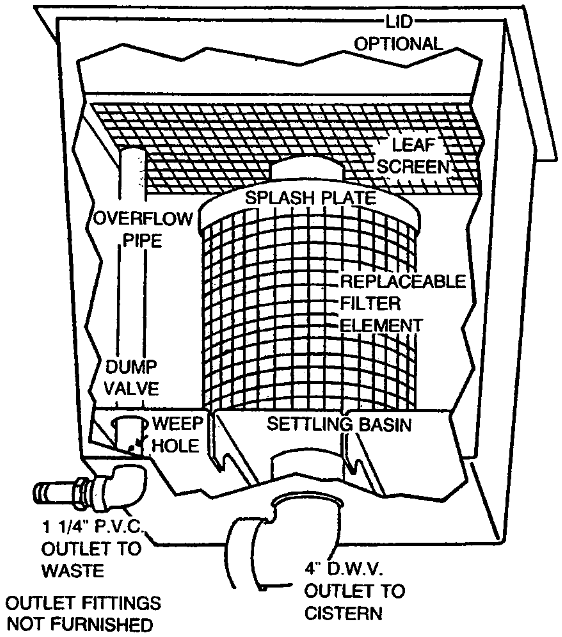


Figure 14. Commercially available filter-type roof washer. (Source: Water Filtration Co. customer information brochure. Water Filtration Co., 108B Industry Rd., Marietta, Ohio 45750.)

stone is used for the gravel and stone portions of the filter.

One possible design for a roof-water filter was pictured in Figure 6. The filter box could be totally or partially buried underground to lessen the chances of freezing during the winter months. The filter box shown in Figure 6 is of reinforced concrete with walls and top a minimum of 4 inches thick. A short section of precast concrete culvert pipe could also function as a filter box; a lid or top would be required, however. A manhole and cover similar to that described previously for the cistern itself should also be built into the top of the filter box to provide access for periodic inspection and maintenance. If the filter box is positioned directly on top of the cistern, as shown in Figure 6, be certain that there is a watertight seal where the two join.

Several layers of gravel and sand will make up the filtering medium. The total thickness of the filtering material should be a minimum of 12 inches and a practical maximum of around 3 feet, depending upon the area of the catchment and size of the filter box. A filter the size of that shown in Figure 6 would be adequate for a roof area of up to 2000 square feet for all but perhaps the most intense rainfalls. For this reason, an overflow should also be built into the filter box, as shown in Figure 6. Mesh hardware cloth (1/4- to 1/2-inch) or aluminum screening is placed on the bottom of the filter box (on the inside) before the gravel and sand are placed. This will keep the filtering material in place.

A cross-section of a typical roof-water filter is shown in Figure 15. Sizes and depths of the sand and gravel layers are shown in detail. Limestone should be used for the gravel and stone portions of the filter. Clean filter sand and gravel must be used, and the entire filter box should be cleaned and disinfected before the sand and gravel are placed. The completed system should also be disinfected with chlorine. Before placing the filter sand and gravel, wash down the interior of the filter box with a disinfecting solution of 1/4 cup of 5 percent chlorine bleach mixed with 10 gallons of water. Use a brush to thoroughly wash all interior surfaces. After the sand and gravel are in place, a gallon of 5 percent chlorine bleach should be added to the filter, the filter filled with clean water and allowed to stand for 24 hours. After this period of time, the chlorine solution should be drained from the filter and clean water should be run through the filter until the chlorine smell dissipates and the water is clear.

A perforated splash plate is also pictured in Figure 15. It is located approximately 2 inches above the top of the sand and serves to break the force of the incoming water, spreading it evenly over the top of the filter sand. In this way the sand will be disturbed as little as possible. A nonmetallic material such as wood or plastic should be used as a splash plate. Half-inch holes should be drilled through the splash plate on 2-inch centers. Supports for the splash plate should be built into the walls of the filter box, thus al-

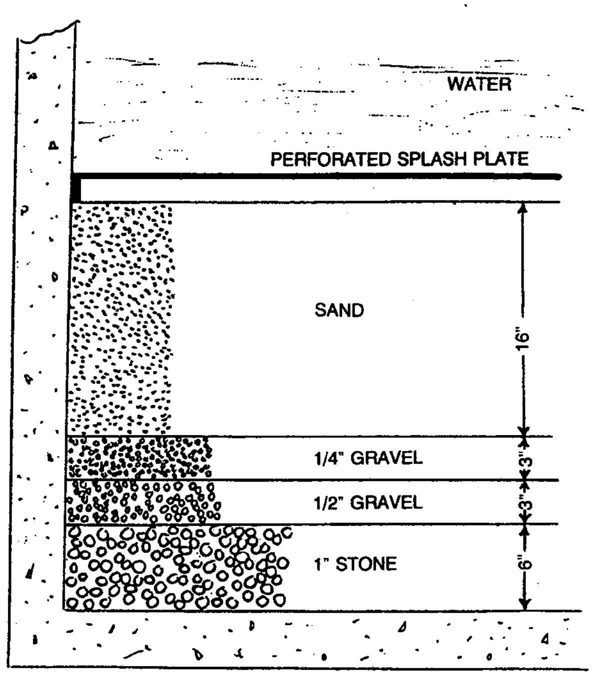


Figure 15. Sand and gravel sizes and depths for a roof-water filter.
(Adapted from Midwest Plan Service, Iowa State Univ. 1968. Private Water Systems., p. 53.)

lowing for easy removal and refitting of the plate for inspection and maintenance of the filter.

Any filter will tend to clog over time and will require periodic maintenance. This may entail the removal of portions of the filter medium and replacement with new sand or gravel. Whenever such replacement is necessary, the entire filter box should be cleaned and disinfected following the procedure described earlier. Periodic inspection of the roof-water filter in your system should provide visual evidence of a malfunction or clogged condition requiring remedial action.

Roof catchments

As mentioned previously, certain types of roofing materials are more suitable than others for use as collection surfaces for rainwater cisterns. Those most suitable for catchments are asphalt shingle, slate, and sheet metal (tin or aluminum). The following factors should be considered when planning a roof-catchment cistern system:

- Rough-surfaced roofing materials will collect dirt and debris which will affect the quality of the runoff.
- Some painted surfaces, some wood shingles, and some asphalt shingles may impart objectionable taste or color.
- All gutters and downspouts should be easy to clean and inspect.
- The roof area should be large enough to supply the amount of water needed.
- The atmosphere in your area may contain undesirable or harmful pollutants that might affect the quality of the collected rainwater.
- Before using a roof coating, consult local health authorities concerning possible toxicity of the material.

Gutter guards should also be installed along any roof catchment. Aluminum screening or 1/4-inch or 1/2-inch mesh hardware cloth can be cut into strips and secured over the top of open gutters, as shown in Figure 16. Gutter guards will keep leaves, twigs, and animals out but let water in. Also remove any tree limbs overhanging the catchment. You may also want to remove nearby trees that contribute leaves and twigs to the catchment; or, if you're planning a new home and cistern system, don't plant trees right next to the house.

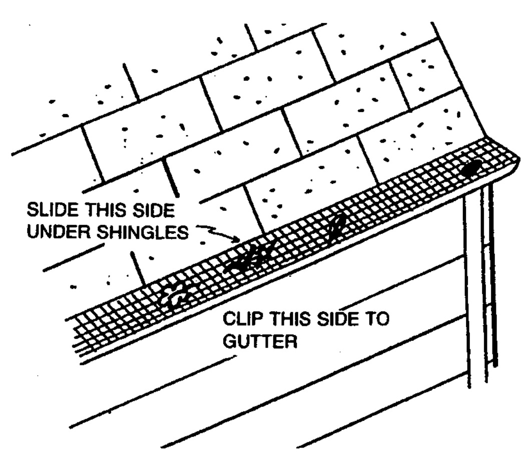


Figure 16. Gutter guard.
(Source: Midwest Plan Service, Iowa State Univ. 1968. Private Water Systems p. 14)

Cistern water treatment

Several of the design features described previously will help insure good-quality cistern water. These would include roof washers, roof-water filters, gutter guards, water force breakers, and effectively screened cistern inlets and outlets. In addition to these measures, however, specific water treatment will be necessary to insure safe, potable cistern water. Recommendations for disinfection of cistern water and minimization of corrosion and sediment transport within distribution systems will be covered in the following pages.

Disinfection of cistern water

The interior of a new cistern should be scrubbed down with a disinfecting solution of chlorine and water, as described for roof-water filter boxes. CAUTION: make sure there is adequate ventilation while working inside the cistern because of the dangers of chlorine gas and lack of oxygen. Following the disinfecting operation, and before filling with water, the interior of the cistern should be rinsed down with clean water until the strong odor of chlorine is no longer present. A cistern should also be disinfected following cleaning or other maintenance that requires emptying the cistern.

To disinfect stored cistern water the simplest procedure is to add Clorox or other 5 percent chlorine bleach once a week, at the rate of one ounce per 200 gallons of stored water during dry periods, or one ounce for each 400 gallons of stored water during wet spells. If a chlorine taste develops in the water it may be reasonably safe to dose weekly with one ounce for each 400 gallons of stored water. If, due to the absence of occupants, water is not chlorinated for a week or longer, one ounce of chlorine bleach for each 200 gallons of stored water should be added to the cistern upon returning.

You can devise a simple way of measuring the volume of water stored in your cistern. A wooden pole, long enough to reach the bottom of the cistern through the manhole opening, should be obtained. The pole can then be calibrated such that when it rests on the bottom it will indicate the approximate volume of stored water from the depth of the water. This can be done in the following way. First, find the capacity of your cistern from one of the two tables at the back of this booklet. If your cistern is rectangular in shape, rather than square or circular, you can determine its capacity by the following procedure. Multiply the length by the width by the depth (all in feet) to get the number of cubic feet of storage. Then multiply this figure by 7.5 to get the number of gallons of storage capacity. For example, a cistern measuring 10 feet by 8 feet, with a depth of 6 feet, would have a storage capacity equal to (10 X 8 X 6) X 7.5, or 3600 gallons.

Once you have determined the capacity of your cistern, the pole can be calibrated according to the following example. To calibrate a measuring pole for a cistern that measures 10 feet by 8 feet, with a depth of 6 feet, first divide the capacity by the depth in inches to obtain the number of gallons per each 1-inch-thick layer of stored water (3600/72 or 50 gallons in this example). Then simply mark the pole at 1-inch intervals, starting at one end and going toward the other until the total depth of the stored water is reached (6 ft. or 72 inches in this example). At each 1-inch interval mark the corresponding volume, starting (at the bottom) with 50, 100, 150, 200, . . . etc., adding 50 (for this example) to each successive interval.

Once calibrated, such a measuring stick would give you a quick way of estimating the volume of water remaining in the cistern at any given time. Depths and corresponding volumes also could be listed side by side in a simple table, and the stick would then only be used to measure the depth of water in the cistern. Chlorine dosages required could also be listed alongside the various volumes for quick reference.

If the water has disagreeable taste and odor, the following procedure may be used. Add 2 ounces of crystallized sodium thiosulfate (available from Fisher Scientific or other supply houses) to 1 gallon of clean water. Then add 1 quart of this solution to each 1000 gallons of water in the cistern, mixing it with the cistern water but being careful not to stir up bottom sediment. After a few hours the water should be free of the disagreeable taste and odor.

Any water supply should be tested for bacterial contamination at least once a year. If a water analysis shows that the water is contaminated, a careful examination of the entire water supply system and of the area surrounding the cistern has to be made in order to find and eliminate the source of contamination.

As an alternative to adding disinfectant directly to the cistern, commercially distributed in-line automatic chlorinators are available from most distributors of water conditioning equipment. The Water Filtration Co. referred to earlier makes one they claim cannot clog up, a problem common to most automatic chlorinators. However, their unit requires an additional pump, adding considerably to the cost of installing such a chlorinator.

Minimizing corrosion within cistern water systems

As pointed out previously, rainwater is acidic and therefore corrosive. Unless steps are taken to neutralize this water, it will corrode household distribution systems adding toxic metals such as lead and cadmium to the tapwater. Corrosion processes are very complex chemical reactions that involve many different factors. Employing the recommendations presented here will not completely eliminate corrosion within your cistern system, but should reduce it to tolerable levels. Minimizing the amount of corroded metals in the finished tapwater is the goal.

Perhaps the surest way of minimizing tapwater metals is to use plastic pipe to service at least one cold-water tap within the system. This would effectively replace the source of metallic lead and copper (lead-soldered copper pipe is the most common type of plumbing for household systems) with a nontoxic, noncorrodible conduit of PVC plastic. Be sure to use plastic pipe that meets specifications for conveying drinking water, if that is what you intend to use it for. If just one cold-water tap within your household were to be serviced by an all-plastic water line, then you should draw *all* of your *drinking* water from that tap and from no other. It would probably be best to plumb the kitchen cold-water tap and perhaps a bathroom lavatory with plastic. If you are planning a new system from scratch, then you may want to consider using plastic plumbing throughout the entire distribution system.

If your existing distribution system is composed of lead-soldered copper plumbing throughout, and you do not want to replace a portion of it with plastic, an alternative would be to install an in-line acid neutralizer to reduce the corrosivity of the water. Such units are available commercially from water treatment equipment distributors located throughout Pennsylvania. The acid-neutralizing units are in the \$600 to \$800 price range and are available in either manual or automatic models.

In lieu of an in-line acid neutralizer, a neutralizing agent could be added directly to the cistern. Following is a table of common alkali reagents along with approximate treatment rates. They are listed in order from lowest to highest cost per pound.

Reagent	Chemical formula	Amount required to neutralize 1000 gallons of rainwater
Limestone	$CaCO_3$	2 oz.
Quick lime	CaO	1 oz.
Hydrated lime	$Ca(OH)_3$	1 oz.
Soda ash	$NaCO_3$	1 oz.
Caustic soda	$NaOH$	1.5 oz.

It would be necessary to add the appropriate amount of neutralizing agent at periodic intervals, depending on the amount and frequency of rainwater input to the cistern. Perhaps the most convenient treatment procedure would be to add the neutralizing agent when you add disinfectant to the cistern (once a week), at least during weeks when additional rainfall is collected. During weeks when little or no fresh rainwater is collected it would *not* be necessary to add more neutralizer to the cistern.

Some cistern owners have placed blocks of natural limestone in their cisterns to serve as continuous neutralizing agents. We have no guidelines to offer you as to the size or other characteristics of such blocks.

Regardless of whether or not you install an acid neutralizer or plastic pipe, or add a neutralizing agent directly to the cistern, there is one simple thing that you should do before using the tapwater for drinking or cooking purposes. You should always allow the cold water to run for about a minute before using it for drinking or cooking. This will flush the "stale" water (laden with toxic metals if from lead-soldered copper or other metallic pipe) from the supply line, leaving you with tapwater of acceptable quality. This practice is especially important after a tap has gone unused for several hours, or overnight. Rather than just letting the water run down the drain during this procedure, you may use it for purposes other than drinking or cooking.

Minimizing sediment transport through cistern systems

Use of roof washers and roof-water filters, described in detail earlier, will minimize the input of particulate matter to the cistern. However, these devices will not completely eliminate input of fine particulates or the formation of a sediment layer on the bottom of a cistern. Therefore, certain steps need to be taken to prevent this sediment from being transported through the distribution system and possibly reaching the tap.

Periodic cleaning of the cistern to remove the sediment accumulation is recommended. This would involve draining the cistern, scooping out the sediment, and washing down the interior with a brush and disinfectant. Thorough rinsing with clean water should precede refilling of the cistern. Such cleaning should be done at regular intervals every three to five years. Applying a new coat of interior sealant may also be necessary at the time of cleaning.

An in-line sediment filtering unit, like those distributed commercially by either of the two companies listed previously for acid neutralizers, should be installed between the cistern and tap to remove any sediment that might otherwise be transported to the tap. Such units are in the same price range as acid neutralizers, and some units are available as a combination acid neutralizer/sediment filter.

Summary statement

This publication is intended to serve as a guide to homeowners who are planning to build a roof-catchment cistern system. It will also provide useful information to those who already own a rainwater cistern and want to improve the quality of the water used. The material presented here has been consolidated from scientific research, public agencies, and private firms specializing in domestic water systems. The cistern study that formed the basis for this publication was conducted in rural Clarion and Indiana counties, Pennsylvania during 1979 and 1980, under the direction of the School of Forest Resources, the Environmental Resources Research Institute, and Penn State Cooperative Extension. Funding was provided through Title V of The Rural Development Act.

References

Information in this circular has been adapted from the following publications:

Contribution No. 173, "Feasibility of Rainwater Collection Systems in California," by David Jenkins and Frank Pearson. Available from California Water Resources Center, University of California, 475 Kerr Hall, Davis, California 95616.

Customer information brochure. Water Filtration Co., 108B Industry Rd., Marietta, Ohio 45750.

Private Water Systems. Midwest Plan Service, Iowa State University, Ames, Iowa 50010, attn. Extension Agricultural Engineer.

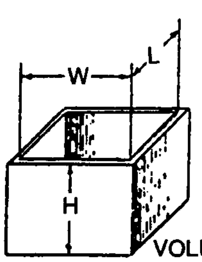
Cisterns for Rural Water Supply in Ohio by Norman G. Bailey. Water Resources Center, The Ohio State University, 1791 Neil Avenue, Columbia, Ohio 43210

CAPACITY (gallons) OF SQUARE CISTERNS

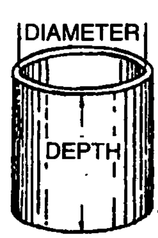
AREA IN FEET	DEPTH IN FEET 4	5	6	7	8	9	10	11	12	13	14	15	LENGTH OF ONE SIDE
16	480	600	720	840	960	1080	1200	1320	1440	1560	1680	1800	4
25	750	937	1125	1312	1500	1687	1875	2062	2250	2437	2625	2812	5
36	1080	1350	1620	1890	2160	2430	2700	2970	3240	3510	3780	4050	6
49	1470	1837	2205	2572	2940	3307	3675	4042	4410	4777	5145	5512	7
64	1920	2400	2880	3360	3840	4320	4800	5280	5760	6240	6720	7200	8
81	2430	3037	3645	4252	4860	5467	6075	6682	7290	7897	8505	9112	9
100	3000	3750	4500	5250	6000	6750	7500	8250	9000	9750	10500	11250	10
121	3630	4537	5445	6352	7260	8167	9075	9982	10890	11797	12705	13612	11
144	4320	5400	6480	7560	8640	9720	10800	11880	12960	14040	15120	16200	12
169	5070	6337	7605	8872	10140	11407	12675	13942	15210	16477	17745	19012	13
196	5880	7350	8820	10290	11760	13230	14700	16170	17640	19110	20580	22050	14
225	6750	8437	10125	11812	13500	15187	16875	18562	20250	21937	23625	25312	15
256	7680	9600	11520	13440	15360	17280	19200	21120	23040	24960	26880	28800	16
289	8670	10837	13005	15172	17340	19507	21675	23842	26010	28177	30345	35512	17
324	9720	12150	14580	17010	19440	21870	24300	26730	29160	31590	34020	36450	18
361	10830	13537	16245	18952	21660	24367	27075	29782	32490	35197	37905	40612	19
400	12000	15000	18000	21000	24000	27000	30000	33000	36000	39000	42000	45000	20

CAPACITY (gallons) OF CIRCULAR CISTERNS

DIAMETER IN FEET	DEPTH IN FEET 4	5	6	7	8	9	10	11	12	13	14	15
4	378	472	566	661	755	850	944	1038	1133	1227	1322	1416
5	590	737	885	1032	1180	1327	1475	1622	1770	1917	2065	2212
6	850	1062	1274	1487	1699	1912	2124	2336	2549	2761	2974	3186
7	1156	1445	1735	2024	2313	2602	2891	3180	3469	3758	4047	4336
8	1510	1888	2266	2643	3021	3398	3776	4154	4531	4909	5286	5664
9	1908	2385	2863	3340	3817	4294	4771	5248	5725	6202	6679	7156
10	2360	2950	3540	4130	4720	5310	5900	6490	7080	7670	8260	8850
11	2856	3569	4283	4997	5711	6425	7139	7853	8567	9281	9995	10708
12	3398	4248	5098	5947	6797	7646	8496	9346	10195	11045	11894	12744
13	3988	4985	5983	6980	7977	8974	9971	10968	11965	12962	13959	14956
14	4626	5782	6938	8095	9251	10408	11564	12720	13877	13033	16190	17346
15	5310	6637	7965	9292	10620	11947	13275	14602	15930	17258	18585	19913
16	6006	7516	9026	10537	12047	13558	15068	16578	18089	19599	21110	22620
17	6820	8526	10230	11936	13641	15346	17051	18756	20461	22166	23871	25577
18	7646	9558	11470	13381	15293	17204	19116	21028	22939	24851	26762	28674
19	8520	10650	12779	14909	17039	19169	21299	23429	25559	27689	29819	31949
20	9440	11800	14160	16520	18880	21240	23600	25960	28320	30680	33040	35400



VOLUME (GALS) = (L X W X H)7.5

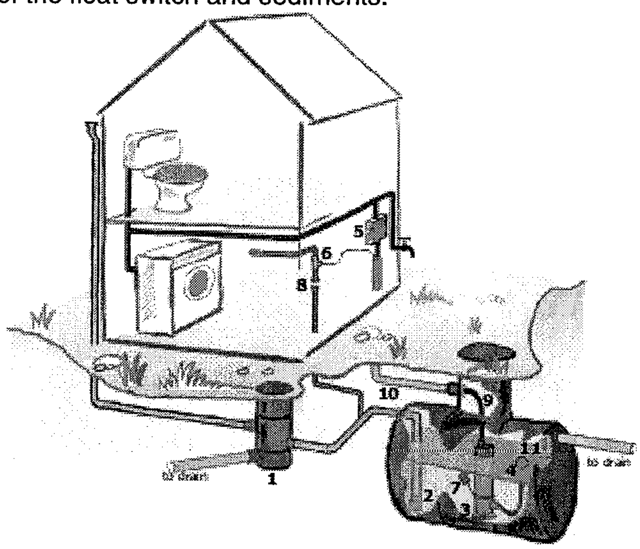


VOLUME (GALS) = $0.785(DIA)^2(DEPTH)7.5$

TYPICAL COMPONENT SYSTEM

How a typical component system, using a submersible pump and underground filter, works.

- Rainwater is collected from the roof and processed by the WISY WFF vortex filter (1). About 85% is diverted into the storage tank with debris and remaining water to soakaway or storm drain in the normal manner. Smoothing inlet (2) calms the flow and prevents disturbance of the float switch and sediments.
- Submersible pump (3) delivers water on demand via a floating suction filter (4) to WC, washing machine and garden tap. Combined pressure switch/flow controller (5) turns the pump on and off when required and provides dry-running protection.



- Float switch (7) controls solenoid valve (6) to provide mains water top-up via a type 'A' air gap tundish (8) (compliant with current water regulations).
- Pressure hose (9) and cables are ducted to the house through a 110mm drainage pipe (10).
- Overflow trap (11) prevents foul odours from drains.

Rainwater Harvesting Systems

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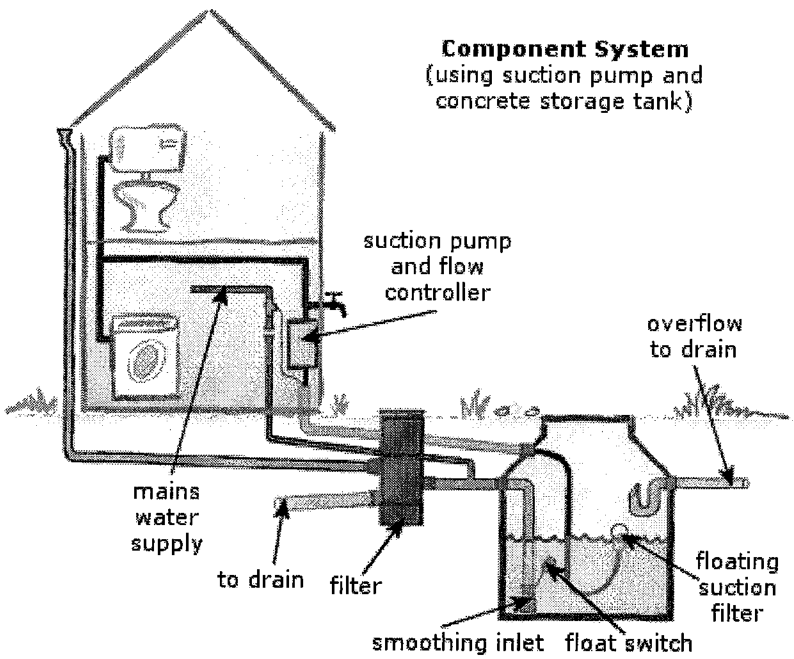
COMPONENT SYSTEM

Illustration of a component system using a suction pump and concrete storage tank.

These systems enable custom-building from separate components. The range of components available gives great flexibility enabling the system to be adapted for many situations regardless of location of the storage tank relative to the building.

Basic component systems with very cost-effective and simple controls are also available for smaller installations supplying perhaps a washing machine and one or two WCs.



Rainwater Harvesting Systems

Typical System
Component System
Module System
Hybrid System
Integrated System
Header Tank System
Garden System
Commercial Systems

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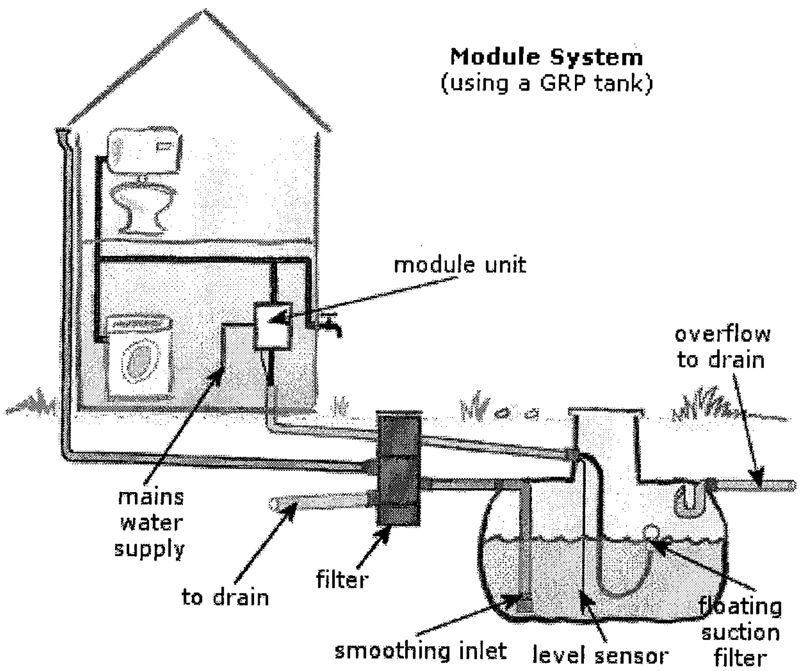
MODULE SYSTEM

Illustration of a module system using a GRP tank.

This type of system differs from the other systems in that they do not replenish the storage tank with mains water. Instead there is an integral mains water cistern which the pump draws from when there is insufficient rainwater in the storage tank. Cistern, pump and controls are assembled into one unit making for easy installation. Module systems usually require a relatively short distance between tank and pump (or suction lift), due to the limitations of suction pumps.
N.B. - In areas with a low mains water flow-rate the pump may deliver water at a higher rate than the integral cistern can be refilled.



Rainwater Harvesting Systems

Typical System
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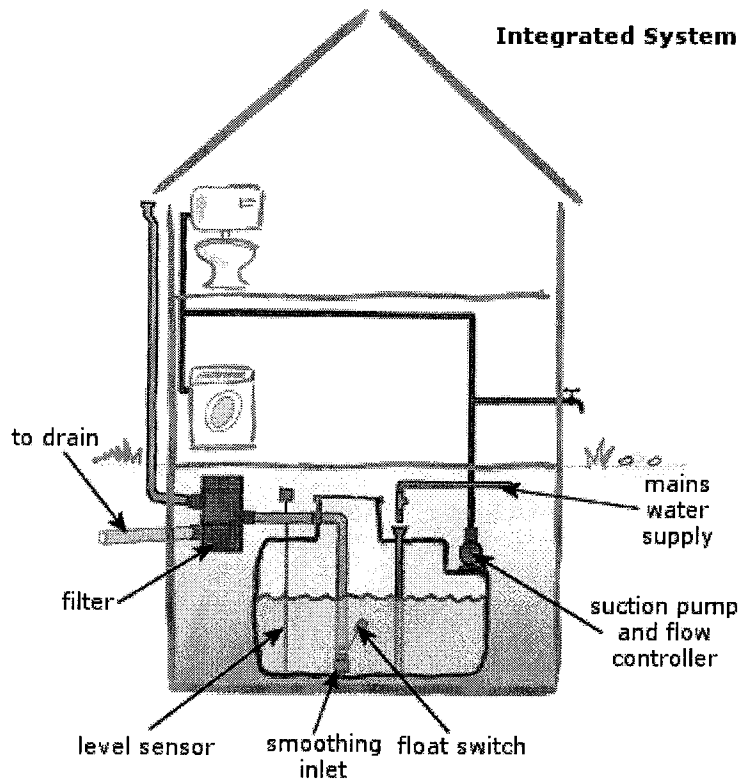
INTEGRATED SYSTEM

Illustration of an integrated rain harvesting system.

These systems combine most of the major components, including the storage tank, into a factory assembled one-piece unit. This significantly reduces time and cost of installation.

Some integrated systems, with the pump and controls mounted on the storage tank, are designed for installation in a cellar or garage. Others are designed for underground use and some have the primary rainwater filter fitted inside storage tank. External controls and mains water top up are still required.



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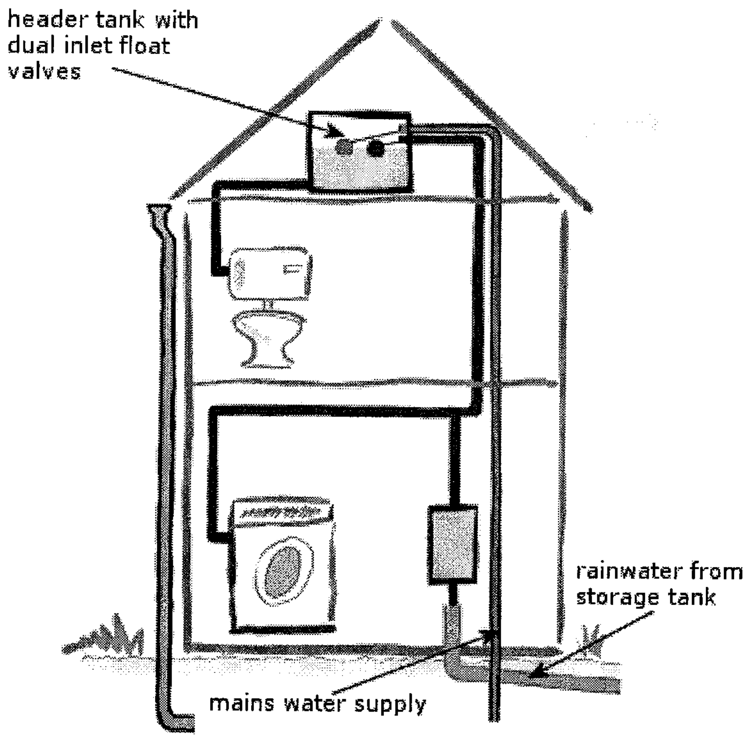
SYSTEMS WITH HEADER TANKS

A header tank can be incorporated into a pumped rain harvesting system.

A variation on a conventional pumped system includes a header tank fitted with dual inlet valves. Rainwater normally fills the tank as long as it is available. When there is no supply from the pump the mains water inlet valve opens. This arrangement can be used to overcome the potential loss of supply to WCs during times of power failure. The washing machine and garden tap are fed directly from the pump as the header tank will give insufficient pressure for these purposes.

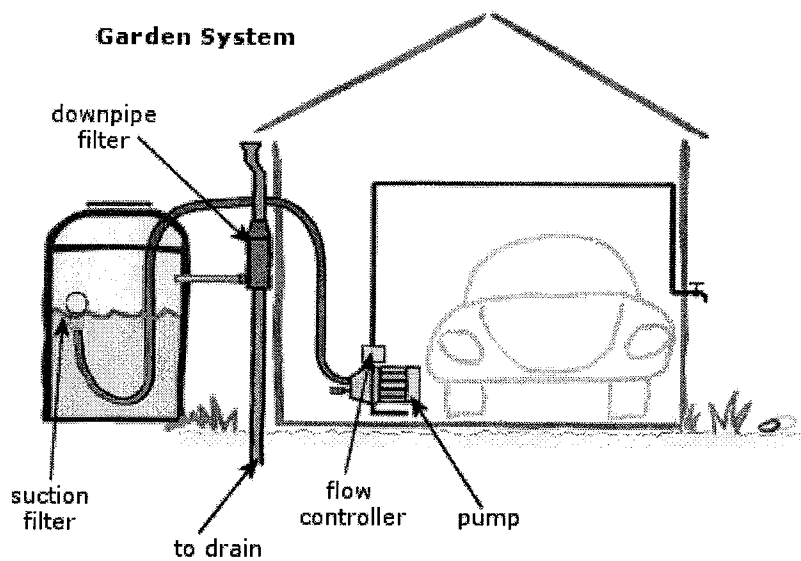


GARDEN SYSTEM

Illustration of a garden system

Using simple proven technology, these systems collect rainwater directly from the downpipe via a highly efficient filter-collector. All but the finest particles are excluded making the water ideal for blockage-free drip feeding in irrigation systems. Filtering also avoids stagnating water making it fit for vehicle and other washing purposes, livestock drinking supplies, etc.

Systems are available for both domestic garden use and for larger commercial irrigation purposes. A basic system can consist of just a filter, tank and pump; dry run protection and/or automatic mains top-up can be added.



Rainwater Harvesting Systems

Typical System
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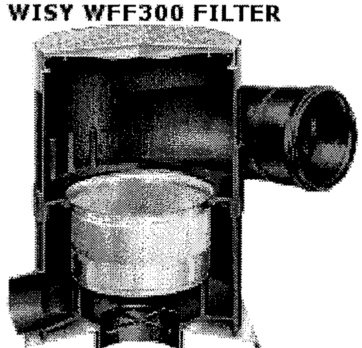
COMMERCIAL SYSTEMS

Introduction to commercial scale rainwater harvesting systems.

The economics of rainwater harvesting in industrial and commercial situations can often be significantly greater than in household installations, due to the generally higher demand for non-potable water. When there is also a large roof catchment area available, there are substantial savings to be made. These savings can be improved upon further by the installation of water-efficient WCs and urinals and other water saving devices such as flow regulators, tap aerators, etc.

Commercial systems are usually larger, more sophisticated versions of those previously described. The facility to monitor both mains and rain water can be included. Components will be larger, sized on supply and demand of water required. Stormwater attenuation may also be designed into the system as well as a reserve supply for fire-fighting for large industrial buildings. Additional filtration in the form of fine sediment filtration and ultraviolet sterilisation can also be included to achieve water of potable quality.

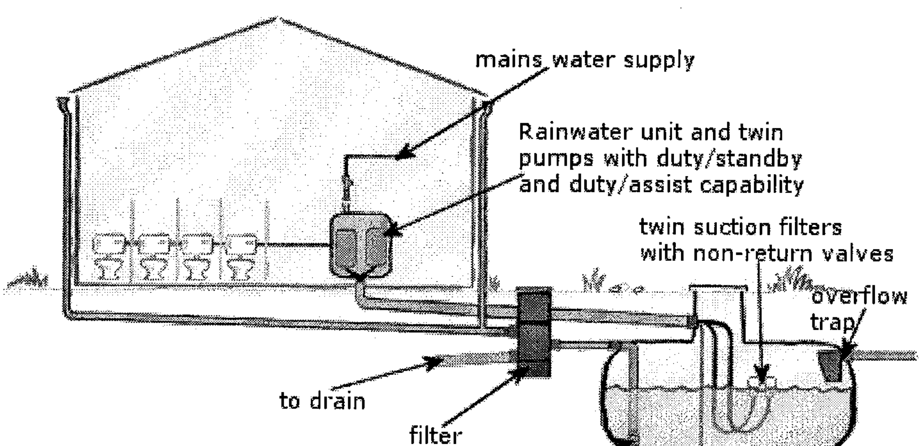
WISY WFF300 FILTER



one filter can collect from a 3000m² roof

Such systems can be used for a variety of commercial uses; plant nurseries and garden centres, vehicle washing plants, agricultural uses, WC and urinal flushing in offices, schools and other public buildings.

Commercial System



Rainwater Harvesting Systems

Typical System
Component System
Module System
Hybrid System
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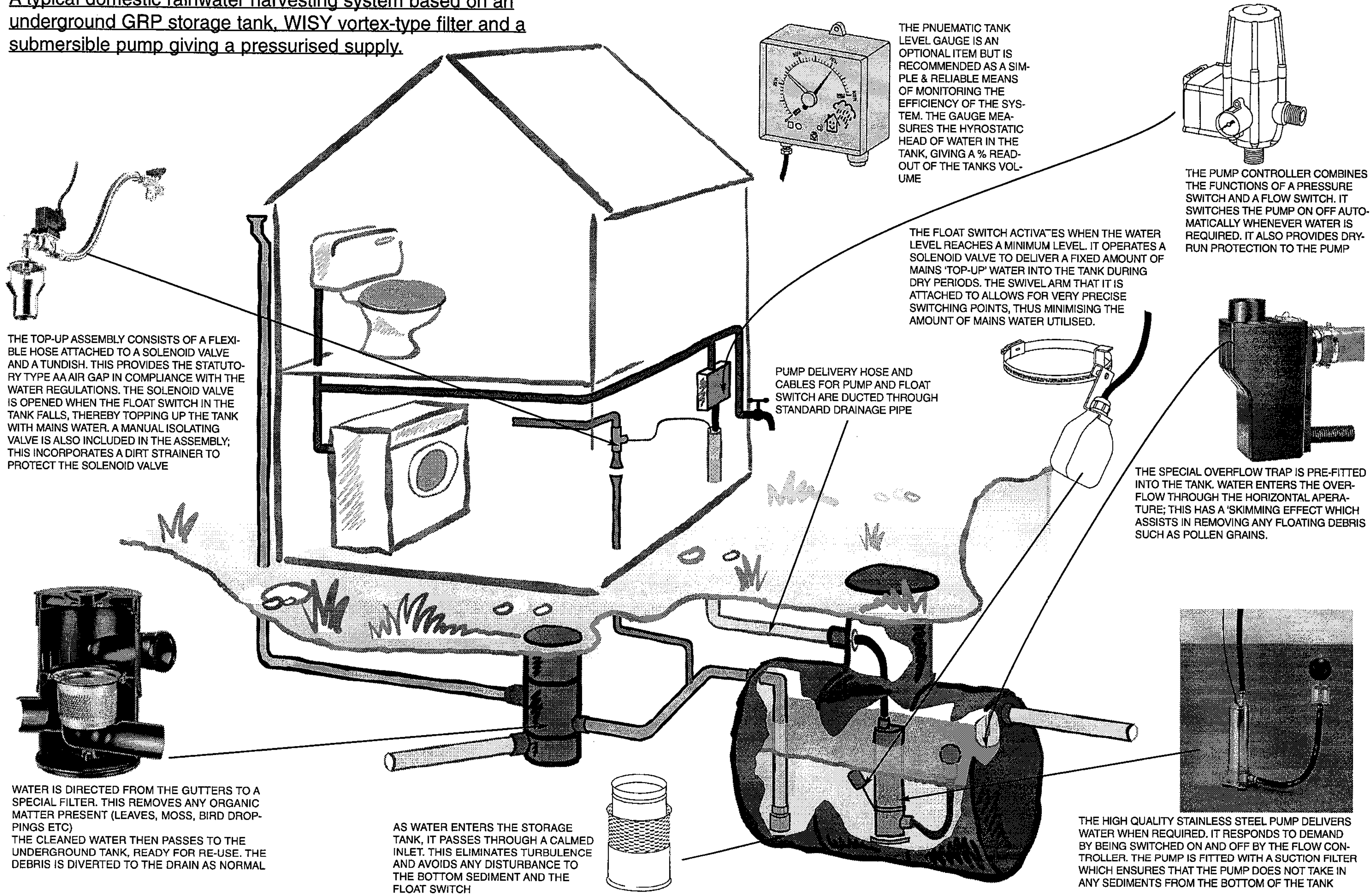
Header Tank System
Garden System
Commercial Systems

<u>A typical domestic rainwater harvesting system based on an underground GRP storage tank, WISY vortex-type filter and a submersible pump giving a pressurised supply.</u>



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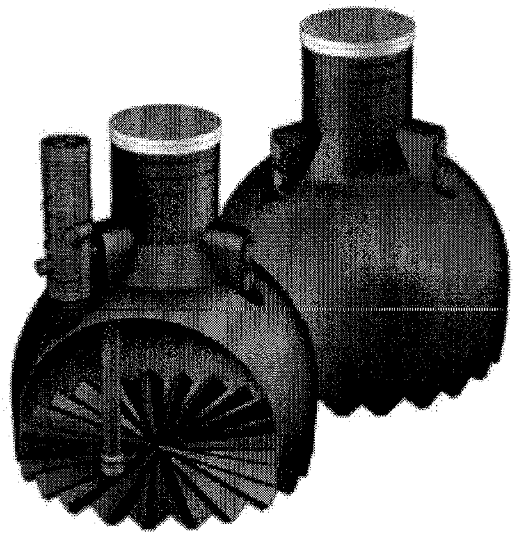

WISY Rainwater Storage Tanks

- Compression-resistant 4000 litre container, carries vehicles up to 12 t
- All-round use because of the multiple connections
- Smooth walls inside prevent deposits and thus improve hygiene and water quality
- Fast and easy installation through plug-in connections
- Lockable, non-slip, child-proof manhole cover
- Possible to connect several WISY rainwater storage tanks into one unit

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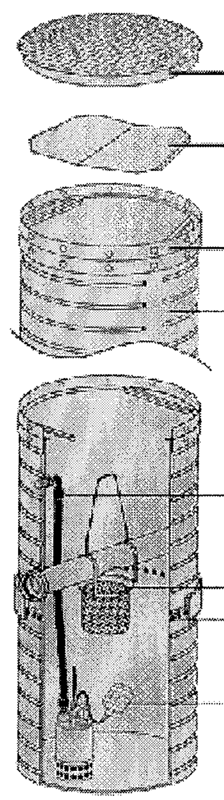


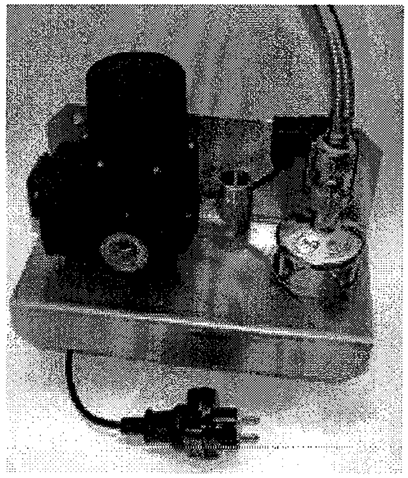
Soakaway Unit

For infiltration of rainwater on the surface

- Soaking away in intervals
- stable construction, carries cars (depending on version)
- low maintenance
- no drain connection necessary
- child-proof cover, anti-skiding
- frost-proof
- useable as elevater unit

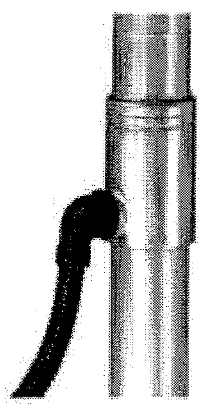
Multimat rainwater unit
Fixed in no time:

- complete supplytechniques for a rainwater installation
- free of suctionpipe problems
- high supply and functional safety
- automatic potable water feed
- cost saving, high quality
- completely noiseless inside the house



The OPTIMA Rainwater Unit

- The most compact basic size
- Innovative basic hydro-mechanical principle
- With fine suction filter
- Safe operation
- Saves costs

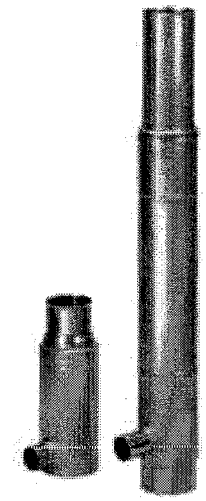


Rainwater Collector

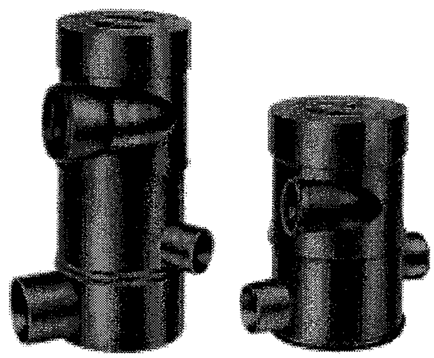
- Collects the rainwater from the roof and leads it into the rainwater barrel
- For fitting into the rainwater downpipe
- Especially for use in gardening

Filter Collector (FS) and Standpipe Filter Collector (STFS)

- For fitting into the vertical rainwater downpipe
- For roof areas of up to about 150 sm
- The unique construction of the vertically sitting fine filter washes out large and fine dirt (larger than 0.28 mm). Moss, leaves and insects are automatically washed into the drain
- Absolutely safe function
- 90% of the water is extracted

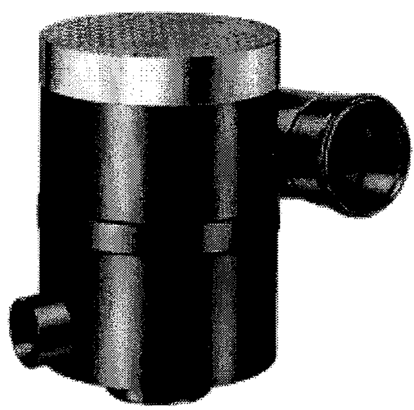


- Meets DIN 1986
- Little maintenance



Vortex Fine Filter (WFF 100, WFF 150)

- For connecting to the drain pipe in the ground
- The unique construction of the vertically sitting fine filter washes out large and fine dirt. Moss, leaves and insects are automatically washed into the drains.
- Absolutely safe function
- 90% of the water is extracted
- Meets DIN 1986

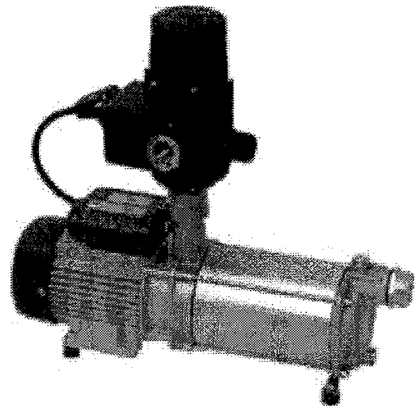


Vortex Fine Filter (WFF 300)

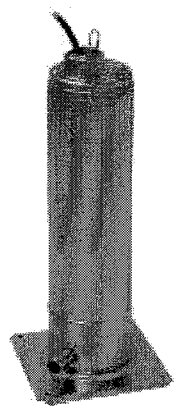
- Ideal for industrial and public buildings
- Large filter water extraction of up to a maximum of 16 litres per second
- Also used for mechanical cleaning of processing water for further use
- Meets DIN 1986

Aspri*PLUS* Suction Pump

- For rainwater use in the house
- For pumping pre-filtered rainwater
- Fast and easy installation
- For connecting to various WISY fine suction filters

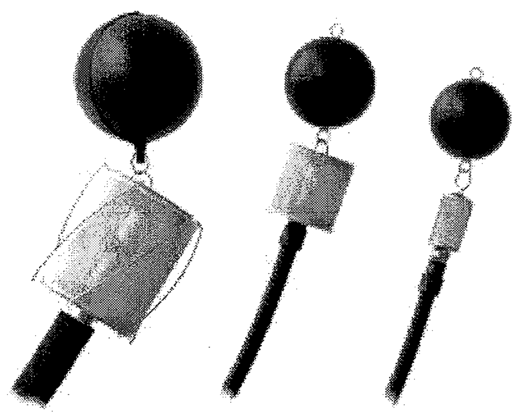


Multigo Pressure Pump



- Multigo pressure pumps bring the pressure from the water directly into the house
- Almost noiseless
- Various suction filters can be assembled on this

Floating Suction Filter

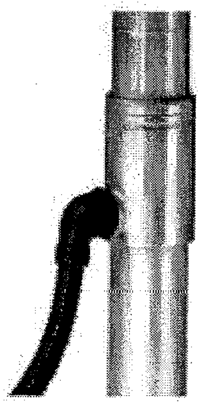


- Water extracted in the cleanest area
- Increases the safety of every rainwater installation
- Protects the pump from pumping sediment

You will find other WISY products here

[Home] [Products] [WISY-SHOP]

Rainwater collector



The rainwater collector

- Top quality in stainless-steel
- Easy fitting into the rainwater downpipe later
- With overflow stop
- Can be connected to any rainwater barrel
- Absolutely safe working at all times of the year
- Extendable with many accessories

Filter* and collect rainwater at the same time

- The WISY rainwater collector filters* / collects the rainwater from the roof and leads it into the rainwater barrel.
- The construction is the same as the patented original WISY filter principle that has proved itself for years.
- You collect only clean water through the vertically placed filter*. Dirt, moss, leaves and insects are not retained but immediately washed into the drain.
- Your rainwater barrel no longer overflows; the automatic overflow inside the rainwater collector sees to that.
- All parts of the rainwater collector are manufactured of rust-free stainless-steel. This guarantees an absolutely corrosion-free and frost-resistant collector.
- Simple care: the stainless-steel filter can be cleaned in the dish-washing machine.
- The rainwater collector can be extended as required (see accessories).
- The rainwater collector is easily fitted into existing downpipes. (please observe the instructions for use).

* Is supplied basically as a "collector" without filter. Extended with item no. 15801 as a filter.

Types

A suitable solution for every rainwater downpipe!

There are rainwater collectors for every downpipe that can be fitted exactly to the nominal size (DN*) of your downpipe and therefore function without any problems.

For rainwater downpipes of metal:
DN 76, 80, 87, 100

For rainwater downpipes of plastic:
DN 70, 100

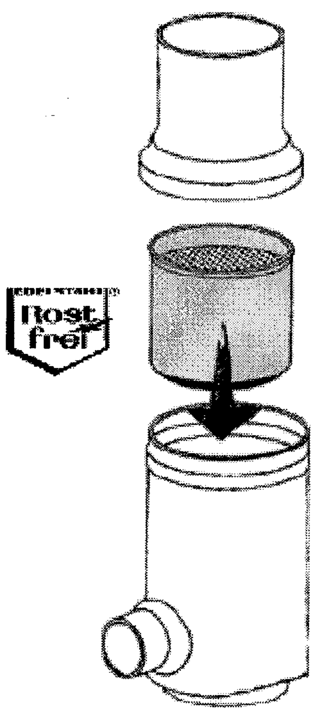
The rainwater collector is easily fitted into the existing downpipe. (please observe the instructions for use).

Simply practical: the rainwater collector with the rainwater barrel connecting hose

* DN = nominal diameter, abbreviation for the nominal size of a pipe (= approximate internal diameter)

Order no. Types of rainwater collectors (RS)

Accessories



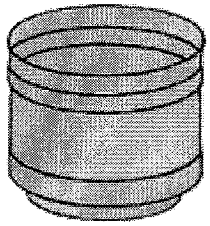
Filter insert
Item no. 15801

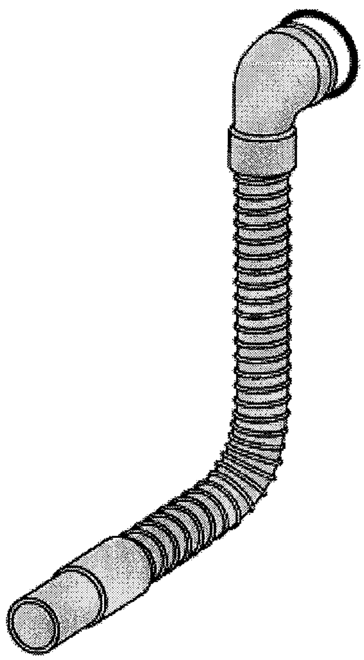
- The filter insert is easily placed in the housing pot.
- The rainwater coming from the roof is additionally cleaned. The rainwater barrel only receives clean water now.
- The unique construction separates leaves, moss, sand and fine dirt (larger than 0.44 mm) and automatically washes these into the drain.

Blind insert
Item no. 15802

- With the stainless-steel blind insert it is possible to stop the rainwater collector. The blind insert is placed into the housing pot for this. (an existing filter insert is to be removed). The rainwater then flows completely into the drain.

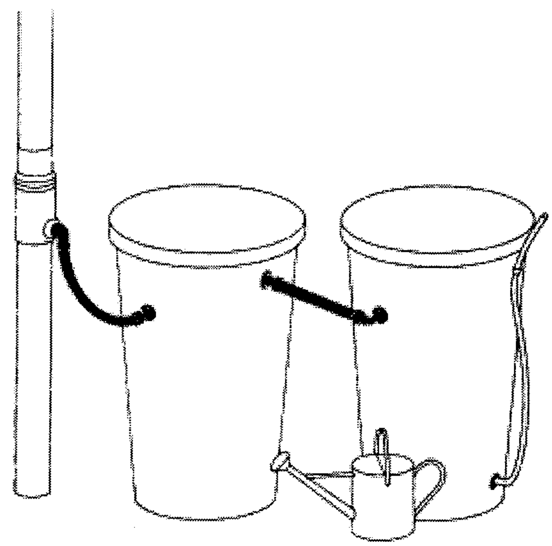
EDELSTAHL® Rost frei

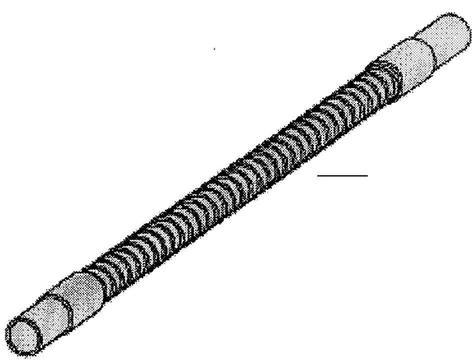




Connecting hose
Item no. 15803

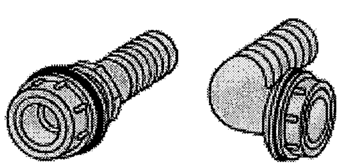
- Connects the rainwater collector to the rainwater barrel connections, UV-resistant plastic spiral hose, 320 mm long, with tension ring.





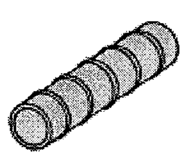
Connecting and extension hose
Item no. 15804

- UV-resistant plastic spiral hose, 320 mm long



Barrel couplings with connectors
Item no. 15805 straight
Item no. 15806 90°

- For direct connection of hoses

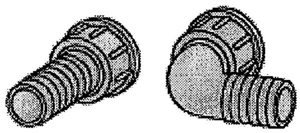


Hose coupling
Item no. 15807

- For connecting two hoses.

Barrel connector
Item no. 15808

- For connecting straight or angled connectors.



Connectors
Item no. 15809 straight
Item no. 15810 90°

- Fits barrel connector 15808. For fitting hoses.

:: close ::

MKA's Bibliographic "Short List" of Internet L.I.D. Sites
Last update: June 30, 2005

L.I.D. overview

http://www.lid-stormwater.net/index.htm

http://www.lid-stormwater.net/soilamend/soilamend_home.htm

http://www.lowimpactdevelopment.org/publications.htm

http://www.sustainabledesignguide.umn.edu/default.htm

http://www.lowimpactdevelopment.org

http://www.epa.gov/owow/nps/lid/

http://www.cwp.org/better_site_design.htm

http://www.cwp.org/22_principles.htm

http://www.stormwatercenter.net

Puget Sound specific
http://www.psat.wa.gov/Programs/LID.htm this is a very good starting point!

http://www.pierce.wsu.edu/Water_Quality/LID/

Bioretention

http://www.ence.umd.edu/~apdavis/Bioret.htm

http://www.psat.wa.gov/Publications/LID_tech_manual05/lid_index.htm

http://www.co.pg.md.us/Government/AgencyIndex/DER/PPD/LID/bioretention.asp

http://www.ci.seattle.wa.us/util/About_SPU/Drainage_&_Sewer_System/Natural_Drainage_Systems/Street_Edge_Alternatives/index.asp

http://www.ci.redmond.wa.us/insidecityhall/publicworks/environment/pdfs/compostamendedsoils.pdf

http://compostwashington.org/PDF/SOIL_MANUAL.pdf

http://www.soilsforsalmon.org

http://www.mapc.org/regional_planning/LID/permeable_paving.html

Porous Asphalt
http://www.hotmix.org

Porous Concrete
http://www.lehighcement.com
http://www.washingtonconcrete.org
http://www.cadman.com

Unit Pavers

http://www.uni-groupusa.org/uni-eco-.htm
http://www.sspco.org/geoblock.html
http://www.invisiblestructures.com

Green Roofs

http://www.greenroofs.ca/grhcc/index.html

http://www.greenroofs.com

http://www.uwm.edu/Dept/GLWI/ecoli/Greenroof/index.html

http://hortweb.cas.psu.edu/research/greenroofcenter/about_ctr

http://www.cleanrivers-pdx.org/clean_rivers/ecoroof.htm

http://www.wbdg.org/design/greenroofs.php

http://www.greenroofs.com/north_American.htm

http://www.greenroofs.ca/

http://www.earthpledge.org/

http://www.ecobuilding.org/

http://www.cleanrivers-pdx.org/pdf/eco_questions.pdf

http://www.hrt.msu.edu/faculty/Rowe/Green_roof.htm

http://www.fll.de/

Green Roof Vendors

http://www.optigruen.de/

http://www.greentechitm.com/

http://www.greengridroofs.com/

http://www.leakdetection.com/

http://www.roofmeadow.com/bondorf.htm

http://www.roofmeadow.com/water_quality.htm

http://www.techaamerica.com/

Rainwater Harvesting

Following includes overview of system components-
http://ag.arizona.edu/pubs/water/az1052/harvest.html

Small scale residential: Experiments in Sustainable Urban Living (Portland)
http://users.easystreet.com/ersson/

State of Texas
http://www.twdb.state.tx.us/assistance/conservation/Alternative_Technologies/Rainwater_Harvesting/Rain.asp

International Rainwater Catchment Systems Association
http://www.ircsa.org/index.htm